# EVALUATING THE SOIL QUALITY OF LONG-TERM CROP ROTATIONS AT INDIAN HEAD

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# ABSTRACT

Crop rotations which differ in fallowing frequency, residues returned and fertilizer additions were hypothesized to have measurably altered the soil physical and biological properties that contribute to a quality soil. This study was initiated to evaluate the role of crop rotation in determining soil organic matter levels and concomitant changes in soil properties.

The rotation site was started in 1958 on a Black lacustrine soil at the Agriculture Canada Experimental Farm, Indian Head, Sk. Rotations of unfertilized fallow-wheat (FW), fertilized fallow-wheat-wheat (FWW(N+P;+straw)), fertilized fallow-wheat-wheat with straw baled (FWW(N+P; -straw)), unfertilized fallow-wheat-wheat-hay-hay-hay (FWWHHH), and fertilized continuous wheat (cont.W) were maintained in a modified randomized complete block design. Cultural practices were fairly consistent over time. Fertilizer additions, after 1977, increased to levels recommended by the Saskatchewan soil testing laboratory. However, the overall mean fertilizer additions from 1960 to 1984 varied only slightly among fertilized rotations.

Systematic transects across the experimental site revealed a major change in soil type occurring in the northern ranges, which was useful in determining a uniform sampling area. Ap horizon thickness and depth to carbonates suggested that topsoil was being removed from the plot areas and accumulating on the grassed roadways.

Continuous wheat and FWWHHH rotations maintained the highest organic C and N concentrations. Soils under FW and FWW rotations contained 13% less organic C and N on average than the cont.W or FWWHHH soils. The amount of light fraction (LF) organic matter and the C:H ratio of the LF were closely related to biological turnover; the LF is a readily available portion of the soil organic matter. Soils under cont.W and FWWHHH contained 1.5 to 2 times more of this active organic matter than those under FWW and FW. Baling straw, reducing fallow frequency, and adding fertilizer did not have a clear impact on total organic matter or the LF.

Mineralization of C, N, and S was statistically more sensitive to reductions in fallow frequency, improved fertility and residue removal. Nitrogen and S mineralization followed a ranking similar to organic C and LF-C contents, with cont.W = FWWHHH > FWW (N+P;+straw) > FWW (N+P;-straw) > FW. Soil biological properties in the 7.5 to 15 and 15 to 30 cm depths were not affected by long-term crop rotation, except for higher rates of C mineralization under cont.W and FWWHHH.

Soil aggregates were larger and more water stable in the less frequently fallowed cont.W and FWWHHH rotations. Soil organic matter and fertility characteristics were related to soil aggregation, likely through enhanced crop growth and production of roots and fungal hyphae. Sorptivity of water under suction was a sensitive indicator of pore structure. Soils in frequently fallowed rotations had the fewest large pores, whereas cont.W and FWWHHH soils had the most large pores. Long-term crop rotation did not affect soil aggregation below the 7.5 cm depth, except where rotations were sampled directly after forages.

Erosion, estimated by comparing $^{137}Cs$ content in the topsoil, was highly variable but suggested that FW incurred the largest topsoil losses, followed by FWW and cont.W, with the FWWHHH rotation least eroded. Reconstruction of the Ap horizon also indicated that crop rotation had influenced the amount of soil lost. Forage periods and improved trash cover, associated with infrequently fallowed rotations, probably reduced wind erosion. Soil loss from frequently fallowed rotations may be exacerbated by tillage and lateral movement of soil from the plots onto the roadways. Loss of organic matter rich topsoil was negatively related to the level of $^{137}Cs$, implicating soil loss as an important process in depleting organic matter.

Soil quality as indicated by nutrient supply, soil organic matter content and lability, and soil tilth was best in the least eroded, most productive FWWHHH and cont.W rotations. Frequently fallowed FW or FWW rotations resulted in the lowest soil quality, with straw baling and inadequate fertilizer additions of lesser importance to the overall soil quality.

To Karen,

for supporting and enduring

this adventure,

Thanks.

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# 1. INTRODUCTION

A quality soil possesses physical and biochemical properties which do not limit plant growth. Favorable soils have adequate infiltration, aeration, moisture holding capacity, nutrient supply and an unrestricted rooting zone. These soil conditions are strongly influenced by soil organic matter. Hence evaluating changes in soil organic matter and properties controlled by soil organic matter is a useful means of characterizing soil quality.

Maintaining soil quality and soil productivity on prairie soils is a persistent problem. In 1946, University of Saskatchewan field husbandry scientist Manley Champlin noted that "it is worthwhile to give careful thought to maintaining soil productivity, before the soil has deteriorated too much." Today, agriculture researchers and extension workers express the same concern. Have we any answers to the recurring questions about soil deterioration and sustaining soil quality?

Rotations containing legumes or 'soil building' sod crops are a proven solution to sustaining soil organic matter and soil quality. In Saskatchewan, however, moisture often limits the establishment of forages and the success of grain crops after forage breaking. Sensitivity to the risk of drought and crop failure has lead to the widespread adoption of summerfallowing. However, along with the benefits of minimizing the impact of drought are the costs associated with loss of soil quality caused by reduced annual residue inputs, lowered soil organic matter contents, and greater risk of erosion.

A wide variety of crop rotations are feasible in the Black soil zone. Cropping systems which differ in residue inputs, surface exposure and frequency of fallowing will alter the soil organic matter content and, over time, change soil properties influenced by soil organic matter. The long-term changes in soil properties which control productivity and soil quality have not been studied adequately on crop rotations in the Black soil zone. The objective of this research was to evaluate the effect of rotations on soil organic matter and associated soil biological and physical properties which influence productivity and, thereby, soil quality.

# 2. LITERATURE REVIEW

## 2.1 Focus - Lifetimes of learning

Crop rotations have been used for centuries to maintain soil productivity. Lifetimes of observation and research have been accumulated by scientists, naturalists and farmers. Given the extensive studies of cropping systems and soil responses, a truly comprehensive dissertation of the literature is impractical. This review will focus on the general impact of management systems on key biological and physical properties of the soil, rather than isolating specific crop rotations and explaining their influence on soil productivity.

## 2.2 Crop rotations - Long term studies

Crop rotations are commonly defined as planned, yearly successions of crops which are used to sustain productivity. Historically, crop rotations included a series of cash crops, fallow and legume-grass hay crops, each playing an important role in overall productivity. Rotating grain, fiber and root crops alleviates disease and pest problems, while spreading market risks over several crops. Fallowing helped to control weeds and allowed a period for incorporating manure. A three to 6 year period of legume-grass forage was useful in replenishing fertility and improving soil tilth. Cropping sequences of this type have effectively sustained arable land in humid regions for centuries. However, the direct application of these rotations to semi-arid regions does not appear feasible (Clarke and Russell, 1977). Climate, economics, risk attitudes and management complexities have limited the practical implementation of soil building forage-grain rotations in Saskatchewan (Champlin, 1950a).

Crop rotation is an important controlling factor in the long term equilibrium of soil organic matter (SOM). Crop sequence and production determines the type and amount of organic debris returned, while tillage practices influence the rate of microbial decomposition and erosion protection afforded by surface trash. The resultant equilibrium between the gains and losses of organic matter under a given cropping system will impact on SOM content and related soil properties (Parton et al., 1983).

Determining the optimum sequence of crops for a given area is a long term task. Rotation studies must be carried on long enough to allow adequate time for soil properties to respond, while minimizing the variability associated with soils, weather and management. Therefore, reliable inferences regarding the response of soil quality to rotation management requires many years of data (Campbell et al., 1989b).

## 2.3 Soil quality - A working definition

Soil quality has been defined as the soil's ability to sustain, accept, store and recycle nutrients, water and energy (Anderson and Gregorich, 1984). More specifically, a high quality soil should possess both physical and biochemical properties which do not limit crop growth. Anderson and Gregorich (1984) defined the characteristics of a high quality soil and stressed SOM as the key factor. Improved levels of SOM will enhance both nutrient transformations and soil tilth, ultimately resulting in greater yield potential. Over time, this synergistic relationship between productivity, crop residues, SOM and soil quality will magnify the differences between rotations which sustain or deplete SOM. Hence, quantifying the biological and physical parameters controlled by SOM will be a useful estimate of the long-term effect of rotation on soil quality.

## 2.4 Biological properties affected by rotation

### 2.4.1 Soil organic matter levels

Cultivation of prairie soils results in lower residue inputs, enhanced SOM decomposition and a subsequent reduction in C and N contents. The extent of the change in C and N is dependent on the organic residues returned, the decomposition rates of organic matter and the amount of topsoil erosion (Ridley and Hedlin, 1968).

Losses of organic N on the Indian Head Experimental Farm were detected as early as 1905 (Shutt, 1923). Twenty-two years of fallow-wheat cropping had lowered the N content by 30% as compared to virgin sod. Shutt suggested that frequent bare fallow and the lack of sod crops would result in lower fertility and productivity which, in time, could become acute. However, an additional 18 years of cropping on this site reduced soil N only 10% more (Shutt, 1925).

The apparent reduction in the rate of fertility loss with time was substantiated further by Moss and Clayton (1941), who reported soil analyses as part of the soil survey of the Indian Head Experimental Farm. The mean content of soil N was 0.009% lower than the soil N concentration reported by Shutt (1923). The limited loss of N suggested that the SOM content of these soils were near equilibrium.

Newton et al. (1945) also found that N and C were lost from the soil at a slower rate as the length of time under cultivation increased. More importantly, their observations affirmed the role of cropping management in determining equilibrium levels of SOM. Depletion of C and N after 29 years of a fallow-wheat-wheat rotation was twice as large as the loss measured in soils under a grain-fallow-hay rotation at Indian Head.

Haas et al. (1957) drew similar conclusions on the influence of cropping practice on C and N losses. Data from experimental stations in the Northern Great Plains of the U.S.A. indicate that SOM was maintained at the highest levels after 30 years of cropping to either sod or continuous small grain rotations. The largest losses of C and N were incurred on soils under row crop or fallow-small grain rotations. Green manuring had no consistent effect. Moisture limitations, limited N-fixation, and losses of N by leaching and volatilization may explain the poor performance of green manures and forages in rotations. Similarly poor results from legume cropping have been observed in the drier parts of Saskatchewan (Newton et al., 1945; Champlin and Gerrie, 1950). However, in the more moist Red River region of Manitoba legume green manures can retard the rate of SOM and N losses from cultivated thick Black soils (Poyser et al., 1957).

Recent studies have dealt with residues and tillage in an attempt to clearly assess their influence on SOM levels. The long term addition of straw in large quantities, although temporarily depressing nitrate contents, maintains or increases soil N and C levels (Ferguson and Gorby, 1964; Black, 1973; Persson and Mattsson, 1987).

The type of crop residues returned has little influence on soil C levels (Larson et al., 1972). Annual additions of cereal straw, leaves or alfalfa residues at 11780 kg $ha^{-1}$ maintained soil C at similar levels (Sowden and Atkinson, 1968). However, including alfalfa and sod crops in rotations will improve the C and N levels since substantial amounts of residues are added belowground, provided moisture conditions are favorable for stand establishment and plant growth (Bowren et al., 1968). The additional N supplied by symbiotic fixation contributes to the growth and residue inputs of subsequent grain crops (Ferguson and Gorby,1971).

Frequency of fallow years is undoubtedly related to the loss of C and N from cultivated soils (Ferguson and Gorby, 1971; Janzen, 1987b). Determining the effect of fallow frequency on SOM loss by oxidation is complicated by the burial of surface trash and subsequent losses of organic matter by topsoil erosion. Despite this obvious confounding, enhanced SOM oxidation caused by frequent fallowing has been cited repeatedly as the major cause of C and N loss (Shutt, 1925; Newton et al., 1945; Ridley and Hedlin, 1968). However, drawing conclusions about fallowing and SOM oxidation while disregarding C and N losses by topsoil erosion is clearly in error.

The use of stubble-conserving cropping practices such as stubble mulch will maintain higher C and N levels as compared to conventional tillage (Unger, 1968). Evidence from stubble mulch studies indirectly suggests that erosion protection is the key to reduced losses of C and N. Clayey and sandy soils had higher C and N contents under stubble mulch than with conventional tillage, indicating the importance of cover on these erodible soils. Less erodible, medium textured soils had similar C and N contents regardless of tillage practices (Bauer and Black, 1981). This hypothesis is further supported by a recent comparison of benchmark sites sampled in the 1960's and again in the 1980's, which indicated that 50% of the C lost over that period could be explained by soil erosion (de Jong and Kachanoski, 1988).

Changes in total C and N resulting from a particular management may not delineate the change in soil productivity. Janssen (1984) illustrated that changes in N supply were not necessarily related to the changes in total N but rather to the 'active' fraction of total N. Therefore both total SOM content and its labile fractions must be considered when describing the fertility status of soils under differing management.

### 2.4.2 'Active' organic matter

The 'active' fraction of SOM is considered to be the recently added, easily degradable plant and microbial materials that are most effective in contributing plant nutrients. Differentiating SOM into 'active' and 'passive', 'young' and 'old' or 'rapidly decomposable' and 'recalcitrant' fractions is an over-simplification given the extreme heterogeneity in the chemical form and biological availability of SOM (Doran and Smith, 1987). Designating pools by age or relative decomposability is useful in conceptualizing the changes in SOM under crop rotations, and in developing means of documenting such changes. Although no one satisfactory procedure exists, the quantification of microbial biomass, partly humified 'light fraction' and clay associated organic matter are used as relative indicators of the active fraction of SOM (Paul, 1984; Greenland, 1971; Anderson et al., 1981).

#### 2.4.2.1 Soil microbial biomass

Microbial biomass is the living population of bacteria, fungi and actinomycetes in the soil. The microbial biomass is a short term source and sink for nutrients, and serves as the principal agent in the transformation of SOM (Jenkinson and Ladd, 1981).

Microbial biomass is an important organic component, although comprising only one to 8% of the total SOM (Paul, 1984). Recent studies indicate a close relationship between N mineralization potential and the size of microbial biomass, indicating the labile nature of the SOM existing as microbial biomass (Carter and Rennie, 1982; Marumoto et al., 1982; Carter and MacLeod, 1987; Myrold, 1987). Response of soil microbial biomass to changing managements is used as a simple, yet sensitive indicator of potential nutrient supply and soil quality (Nannipieri, 1984; Carter, 1986).

Long-term crop rotations with varying levels of residue addition and/or fertilizer inputs have a definite impact on the size and activity of the microbial biomass. Cropping systems which retain large amounts of residues and have adequate fertilization will maintain a large and active microbial population (Schnurer et al., 1985; Biederbeck et al., 1984).

Legume green manure and forage cropping cycles also increase the size and enhance the activity of the microbial biomass (Bolton et al., 1985; Fraser et al., 1988; McGill et al., 1986; Carter, 1986). Few field studies have critically considered the quantity and the relative decomposability of residues as factors contributing to the size and activity of the microbial biomass. Addition of cereal straw, alfalfa or leaves did not significantly affect the dehydrogenase activity of a Rideau clay soil (Sowden and Atkinson, 1968).

Tillage mixes crop residues into the soil and disrupts aggregates, which in turn exposes organic matter to microbes and stimulates decomposition (Rovira and Greacen, 1957; Lynch and Panting, 1980). Fallow cycles speed decomposition of SOM and the cycling of nutrients, reduce annual residue inputs and, eventually, reduce SOM levels. More importantly, frequently tilled or continuous fallow rotations result in proportionately greater losses in microbial biomass (Schnurer et al., 1985; Biederbeck et al., 1984). These results suggest that the labile organic fraction, responsible for microbial growth and subsequent nutrient turnover, is more rapidly depleted than the total

SOM. Thus, organic matter quality or the proportion of active to total SOM must be considered when evaluating rotation systems (Jenkinson and Ladd, 1981).

2.4.2.2 Clay associated SOM

Five to 25% of the organic C (OC) and N is associated with the fine clay faction (Turchenek and Oades, 1979; Anderson et al., 1981). Particle size fractionation and NMR studies indicate that the fine clay associated SOM is rich in N and S, is highly aliphatic, and composed mainly of plant waxes and microbial by-products (Anderson et al., 1981; Oades et al., 1987; Ahmed and Oades, 1984). This physically stabilized SOM is an important moderately available source of plant nutrients (Anderson, 1979; Anderson and Coleman, 1985; Christensen and Sorensen, 1985).

Turnover of C and N have been used extensively to determine the relative age and activity of clay protected SOM (Chichester, 1969; Ladd et al., 1977; Christensen and Sorensen, 1986). Carbon-14 enrichment of the fine clay fraction 15 years after enhanced radiocarbon deposition by the bomb effect indicates the rapid turnover rate of C in the fine clay fraction (Anderson and Paul, 1984). Long-term cultivation studies yield similar conclusions. There were proportionately greater C losses from SOM associated with the clay fraction after 60 years of cropping, indicating the labile nature of clay associated SOM (Tiessen and Stewart, 1983).

The amount and importance of physically stabilized SOM is affected by both clay content and cropping history (Sorensen, 1981; Christensen, 1987). Loss of C and N from the sand-sized SOM fraction and accumulation in the clay fraction occurred after 20 to 70 years of cultivation on Australian soils (Dalal and Mayer, 1986c & d). This redistribution of SOM into the moderately labile clay-protected fraction supports the hypothesis of Anderson and Paul (1984), who suggested that physically stabilized SOM will dampen the fluctuations in labile nutrients and function as a moderate supply of nutrients in cultivated soils.

2.4.2.3 'Light' fraction of SOM

Soil organic matter, not associated with mineral particles, has a lower density than organo-mineral complexes (< 2 gm $cm^{-3}$) and is known as 'light fraction' (LF) organic matter. Light fraction organic matter is composed of unhumified and/or partially humified plant material, faunal debris, fungal bodies, microbial components, charcoal and amorphous material (Perrott and Sarathchandra, 1987; Spycher et al., 1983; Molloy and Speir, 1977; Oades and Ladd, 1977; Greenland and Ford, 1964). Climate, vegetation and soil texture closely control the amount of LF and its contribution to total soil C and N (Perrott and Sarathchandra, 1987; Molloy and Speir, 1977; Ladd and Amato, 1980). Arable Chernozemic soils contain 10-30% of total C and 2-15% of the total N in the LF (McKeague, 1971; Janzen, 1987b; Shaymukhametov et al., 1984).

Soil organic matter in the LF is readily decomposable and has a strong influence on N turnover (Greenland, 1971). The contribution of LF toward net mineralization of N depends both on the amount and the C:N ratio of the LF (Greenland and Ford, 1964; Sollins et al., 1984; Janzen, 1987b). Nitrogen loss from the LF could explain from 25 to 60% of the N mineralized during a 4 week incubation (Ford and Greenland, 1968). The amount of N mineralized from the LF was larger in a sandy soil than a clayey soil. This proportionately larger contribution of the LF in the sandy soil is likely a result of limited clay protection of microbial by-products and, subsequently, less SOM turnover from the medium term pools (Dalal and Mayer, 1986d). Close relationships between the LF and N mineralized, especially in the initial weeks of incubation, suggest that the LF is an important part of the easily available, rapidly decomposable SOM (Janzen, 1987b; Dalal and Mayer, 1987a & b).

Crop management has a considerable influence on the size and C:N ratio of the LF. The use of fertilizer and reductions in the frequency of fallow increased the proportion of C and N existing as LF (Shaymukhametov et al., 1984; Janzen, 1987b). These management practices increase the amount of residue returned which in turn, increases the quantity of material incorporated into the LF.

In humid regions, legume cropping for longer than two years increases the LF by 2 to 4 times relative to soils in continuous cereal cropping or fallow-wheat systems (Ford and Greenland, 1968; Whitehead et al., 1975). In contrast, legume forage cycles in semi-arid areas do not always increase the amount of N in the LF (Janzen, 1987b). Moisture limitations on the Canadian Great plains can cause poor legume yields, reduced residue addition and less LF accumulation.

Long term (20 to 70 years) cultivation results in an exponential loss of C and N contained in the LF (Dalal and Mayer, 1986d & 1987a). Losses of organic C and N were greatest from the LF (25 to 70%), followed by total organic C and N losses (20 to 45%) and least from the clay-sized fraction (Dalal and Mayer, 1986a & 1987a). Light fraction also declines as the frequency of fallow increases (Janzen, 1987b). This response is expected since both residue inputs are reduced and decomposition is enhanced.

### 2.4.3 Mineralization of carbon, nitrogen, and sulfur

Mineralization of SOM and the subsequent release of C, N and S has received much attention. Although the precise organic substrates and catabolic steps are not fully known, the general cycles of these elements have been adequately described and the modifying factors well reviewed (Campbell, 1978; Biederbeck, 1978; Jansson and Persson, 1982). This discussion will center on the mineralization patterns of soils under long-term rotations and their use in identifying qualitative differences in SOM.

Measures of net mineralization are useful in determining the impact of cultural practices on the turnover and supply of nutrients. Cropping practices alter the activity of the microbial biomass, which is the driving force behind SOM decomposition and nutrient release (Stewart, 1984; Jansson and Persson, 1982). Biological activity is, therefore, a useful index of available or active substrate. This functional approach is more meaningful than the determination of elemental concentrations or chemical separations since the nutrient supplying power of the soil is determined by the microflora and the accessible substrates (Jansson, 1981). However, the success of evaluating soil organic matter quality based on biological activity is limited by the assumption that relatively distinct active and stable pools exist (Paustian and Bonde, 1987). As well, interpretation of soil activity based on net mineralization of N and S, although practical in regards to plant availability, yields little information on the gross amounts mineralized or immobilized (Jansson and Persson, 1982).

Microbial decomposition of organic substrates results in the respiration of $CO_2$ or C mineralization, and the concomitant release of N. Net mineralization of N depends on the C:N ratio of the substrate and the nutrient demand by the expanding biomass. Long term rotations alter the equilibrium level of SOM, the microbial biomass and, therefore, the mineralization of C and N. Mineralizable C and N often show a proportionately larger response to management than total concentrations of C and N. Hence changes in the proportion of mineralizable SOM often indicate an improvement in SOM quality long before large differences are noted in total SOM.

Fertilization of continuous wheat over long periods increased mineralizable C by 29%, whereas total C increased by only 14% (Janzen, 1987a). Frequent fallowing, inadequate fertilization and long periods of exploitive cropping will reduce mineralizable N faster than total N (Janzen, 1987b; Campbell and Souster, 1982; Dalal and Mayer, 1986a). The quality and quantity of residues returned to the system largely influence C and N mineralization (Millar et al., 1936; Black, 1973). Amounts of C and N mineralized are greater in soils amended with legume residues than with cereal residue, except where cereals are grown under high N and S fertility (Janzen and Kucey, 1988). Adequate fertilization and infrequent fallow periods generally improve the proportion of potentially mineralizable N (Campbell et al., 1989a).

Sulfur mineralization is a result of biological and biochemical (enzymatic) breakdown of C-bonded and ester S, respectively (Stewart and Sharpley, 1987; McGill and Cole, 1981). The contribution of biochemical S mineralization, although poorly quantified at present, seems significant in open system incubations where accumulation of sulfate and subsequent biochemical inhibition of S mineralization does not occur (Maynard et al., 1983). Information on S mineralization under open incubation conditions is limited (Tabatabai and Al-Khafaji, 1980; Maynard et al., 1983; Roberts, 1985).

Indian Head Association soils mineralized 11.3 $\mu g\ SO_4^{=}\ g^{-1}$ or 3.6% of the total S, during a 17 week open incubation (Maynard et al., 1983). Loamy textured Black Chernozemic soils released up to 6.4% of the total S over a 27 week incubation period (Roberts, 1985).

Cropping history and residue addition can alter the mineralization of S. Cumulative S mineralized during an 18 week open incubation was significantly larger from a field cropped for ten years to alfalfa than in a similar fallow-wheat field (Cowell, 1985). These results indicate that the active fraction responsible for S mineralization is affected by the type of crop residues. Recent research on the contribution of Brassica napus residue to S mineralization further supports this hypothesis (Janzen and Kucey, 1988). Sulfate mineralization increased as the concentration of S in the crop residues increased.

## 2.5 Physical properties affected by rotation

### 2.5.1 Soil tilth

The physical arrangement of soil particles and the resultant interparticle spaces or pores constitutes the soil structure. Good soil structure or tilth depends primarily on the flocculation and cementation of soil particles into a relatively stable assemblage which will allow free movement of air and water, easy cultivation and unobstructed root growth

(Hillel, 1982). Tilth is often poorly related to final crop productivity since other factors such as biological activity, management and prevailing weather conditions interact to determine the extent to which soil structure will be limiting. Consequently, well-defined critical limits for indices of soil tilth are not practical (Blake, 1980).

A better approach is to evaluate the adequacy of soil tilth with respect to the prevailing weather conditions (de Jong, 1984). For example, under wet conditions a low proportion of coarse, stable aggregates will result in a deficient macropore system thereby limiting infiltration, aeration and, consequently, plant growth. A similar pore system under dry conditions, however, may not limit crop production (de Boodt et al., 1961).

Soil tilth has been studied under various cropping systems using size distribution and stability of aggregates, bulk density, air and water permeability and soil strength. The following sections will focus on the effect of long term cropping practices on the aforementioned soil tilth indices.

2.5.1.1 Soil bulk density

Soil bulk density has been extensively used as a simple index of soil tilth (Vomocil, 1957). Cropping systems which alter residue and SOM levels will result in changes in bulk density, either directly, by dilution of mineral soil with less dense organic matter, or indirectly as a result of aggregation (MacRae and Mehuys, 1985). Improvements in the size and stability of aggregates caused by increased SOM contents and fibrous root systems will lead to more pore space and lower bulk densities (Low, 1955; Oades, 1984; Angers et al., 1987).

Long-term rotations which include forages, manure or straw applications often result in lower bulk densities (or higher porosities) than row crop rotations (Stone et al., 1985; Page and Willard, 1946; Hageman and Shrader, 1979). In rotations dominated by small grains, changes in bulk density caused by forage cropping, cereal residue inputs or manure additions are less consistent (Bowren and MacNaughton, 1967; Spratt, 1966; Ferguson and Gorby, 1964; Campbell et al., 1986). Variation in tillage practices and soil texture can complicate comparisons of bulk density among crop rotations (Hageman and Shrader, 1979; Vomocil, 1957).

2.5.1.2 Aggregate size and stability

Aggregation is a useful measure of soil tilth, since the size and strength of the aggregates determine the extent and stability of the pore space (Oades, 1984). Organic matter is the major cementing agent in temperate soils and, therefore, plays a dominant role in the formation and stability of aggregates.

Not all SOM has the same function in soil aggregation. Microaggregates, arbitrarily defined as those less than 0.25 mm, are held together by strongly humified organic matter and polysaccharides (Tisdale and Oades, 1983). Humified materials form microaggregates which are persistent, while easily synthesized and decomposed polysaccharides result in microaggregates that are transitory. Roots and fungal hyphae effectively bind microaggregates into macroaggregates by drying, compressing and enmeshing the soil mass (Allison, 1968; Tisdale and Oades 1983). This conceptual model of aggregation suggests that crop sequences that include crops with fibrous root systems will result in relatively more macroaggregates of greater stability (Elliott, 1986).

Crop rotations which include sod crops or legume-grass cycles increase the stability of aggregates (Page and Willard, 1946; van Bavel and Schaller, 1950; Low, 1955; Skidmore et al., 1975; Baldock and Kay, 1987). The mean weight diameter of aggregates from long-term rotations containing hay were 1.6 to 2.8 times greater than those from crop-fallow rotations (Toogood and Lynch, 1959; Spratt, 1966). Similarly, Dormaar (1983) found continuous wheat cropping resulted in 30% more water stable aggregates than the two or three year fallow-wheat rotations.

Increasing amounts of residue returned to the soil increases the proportion of water stable aggregates and non-erodible dry aggregates (Morachan et al., 1972; Black, 1973; Biederbeck et al., 1984). The type of crop residues added affects the transient binding agents, but has little persistent effect on aggregate stability (Morachan et al., 1972; Halstead and Sowden, 1968).

Tillage at extremely high or low moisture contents will puddle or pulverize soil aggregates (Hillel, 1982). Therefore, frequent and destructive tillage operations are likely to reduce aggregate size and stability (Power et al., 1958; Douglas and Goss, 1982).

2.5.1.3 Infiltration and sorptivity

Water infiltration into the soil is largely influenced by the amount, continuity and stability of the pore space. Aggregates which disperse upon wetting will cause a reduction in porosity and water infiltration (Oades, 1984). Management practices that enhance the formation of water stable aggregates should increase water infiltration (Skidmore et al., 1975; Fahad et al., 1982). Improved infiltration is not always associated with increases in water stable aggregates because of the large variability in infiltration within fields and the insensitivity of the analytical techniques (MacRae and Mehuys, 1985; Smith et al., 1987).

It is possible to reduce the variability associated with hydraulic properties by applying water under a slight suction, thereby eliminating the overiding effects of spatially variable macropores (Smettem, 1987; Clothier and White, 1981). The gravity gradient acting upon soil water is relatively small when infiltration times are short (Talsma, 1969). Given this situation, the slope of the line relating cumulative infiltration under suction to the square root of time describes the sorptivity ($S_{neg}$) of the soil matrix excluding macropores (Green et al., 1986). When equal moisture contents (soil matric potentials) exist, sorptivity may be used as an index of soil tilth since it is strongly affected by soil structure and porosity (Chong and Green, 1983; Walker and Chong, 1986).

Mapa et al. (1986) first used $S_{neg}$ to characterize changes in soil structure caused by wetting, drying and tillage. Tillage loosened the soil resulting in a large proportion of non-conducting macropores and reducing $S_{neg}$. Conversely, the first wetting/drying cycle increased $S_{neg}$ since compaction and collapse of the larger pores formed smaller pores capable of conducting water under suction.

2.5.1.4 Soil strength

Soil strength is the ability of the soil, at a given moisture content, to resist an applied force (Gill and Vanden Berg, 1967). The tillage force applied must be large enough to overcome soil cohesion, adhesion and soil- implement friction. Soil properties such as size and distribution of aggregates, texture, bulk density, SOM and moisture content have a bearing on the soil response to applied force (Baver et al., 1972). Moisture content is the most important property since cohesion and adhesion are the major forces affecting tillage resistance. Reduced drawbar pull and plow draft in fine textured soils is often observed after forage cycles or other 'structure building' crops (Hillel, 1982; Blake, 1980; Morachan et al., 1972). However, few studies have actually quantified the tillage force requirements under various cropping systems.

Old arable soils required almost twice as much tillage force as the soils recently out of grass (Low, 1972). Significantly lower draft force was required on some Chernozemic soils having legumes in the rotation, with the exception of the Indian Head Association soil (Grevers and de Jong, 1984). Variability in soil texture can confound draft measurements, and mask the effects of crop management (Haines and Keen, 1925a). Consequently, only long term management practices which greatly alter soil properties cause noticeable changes in draft force (Haines and Keen, 1925b). The draft force required for the first cultivation after crop (primary tillage) can be highly variable because of the work required to tear apart the extensive root systems of plants grown in fertile soils (Baver et al., 1972).

2.5.2 Erosion and erosion potential

Erosion and dilution of the Ap with subsoil will damage soil quality and restrict crop productivity through: (i) loss of plant nutrients associated with fine, light, erodible material (ii) loss of available water storage capacity (iii) degradation of soil structure and loss of a favorable rooting zone, and (iv) increased soil anisotropy (National Soil Erosion - Soil Productivity Research Planning Committee, 1981). Therefore, erosion and erosion potential are no less important than changes in soil tilth when considering the physical processes which can reduce soil quality and productivity.

Older studies of soil degradation have recognized the difficulty in assessing management effects on SOM independent of erosion (Shutt, 1923; Moss and Clayton, 1941; Newton et al., 1945). Visual observations were commonly used to select comparative areas where erosion was minimal. However, substantial soil loss may occur before changes are visible in the soil surface or Ap horizon thickness (Kimberlin et al., 1977). Recent studies and predictive models have affirmed that losses of organic C and N by erosion are significant, especially over long cultivation times (Gregorich and Anderson, 1985; Voroney et al., 1981; de Jong and Kachanoski, 1988).

Synergistic relationships between crop rotation, erosion and soil quality are complex and often defy simple interpretation. Cropping sequence affects aggregation and residue coverage, both of which determine the soil's erosion potential. However, soil loss from a potentially erodible soil occurs only when strong winds or heavy rains prevail on a soil surface unprotected by vegetation or residue cover.

2.5.2.1 Estimating net erosion using cesium-137

Cesium-137 is a strong gamma emitting isotope which is tightly held by clay and organic matter. Detonation of thermonuclear devices during the 1950's and 1960's released $^{137}Cs$ into the atmosphere. Precipitation deposited the radionuclide on the soil surface, mainly during the early 1960's (de Jong et al., 1982). Estimates of erosion are obtained by comparing the $^{137}Cs$ content of the study area to that of a control site, supposedly unaffected by erosion or deposition (Pennock and de Jong, 1987). Assuming that $^{137}Cs$ is uniformly distributed in the plow layer, non-selective soil losses (ie. $^{137}Cs$ loss = soil loss) can be estimated. Selective removal of fine silts and clays during wind erosion may lead to overestimates of soil erosion using $^{137}Cs$. However, in heavy textured Indian Head soils, wind eroded sediment is not appreciably enriched in fine particles or organic matter (Moss, 1935).

2.5.2.2 Wind erosion potential

The susceptibility of cropped land to wind erosion is of major concern in semi-arid regions (Skidmore and Siddoway, 1978). Wind erosion is moderated by soil factors, field characteristics and vegetative cover. The two most important factors influencing wind erodibility of a dry bare soil surface are the amount and mechanical stability of soil clods or aggregates (Chepil, 1958). Aggregates greater than 0.84 mm minimal diameter are considered to be non-erodible aggregates since they are too large to be moved by most winds. The density and size distribution of particles > 0.84 mm will also affect their erodibility (Chepil, 1958). Mechanical stability measures the ability of non-erodible aggregates to resist breakdown (Chepil, 1953). Large aggregates having a low mechanical stability will be easily abraded by saltating particles and afford less surface protection than more stable non-erodible aggregates.

Bare soil surfaces containing greater than 55% non-erodible aggregates will resist erosion under most winds (Anderson, 1968). Cropping practices that increase surface residues will increase the proportion of non-erodible aggregates (Black, 1973; Siddoway, 1963; Biederbeck et al., 1984). Including alfalfa in rotations dominated by root crops reduced the proportion of wind erodible aggregates (Mazurak et al., 1953). Conversely, legume forages rotated with fallow-wheat increased the proportion of erodible aggregates relative to the fallow-wheat rotation (Siddoway, 1963).

Non-erodible aggregates are also affected by tillage frequency and the type of implement used. One-way discing and plowing pulverizes dry aggregates more than subsurface tillage tools (Power et al., 1958). However, some degree of mixing of surface residues is required to promote the formation of non-erodible aggregates (Smika and Greb, 1975). Frequency of tillage and tool design also determines the degree of surface cover (Anderson, 1968).

Vegetative cover effectively protects the soil surface from erosive forces (Skidmore and Siddoway, 1978). The threshold level of residue required to prevent erosion on a particular soil depends on the residue type and orientation (Chepil and Woodruff, 1963; Anderson, 1968). Standing residue is more than twice as effective in erosion control as flattened residues (Skidmore and Siddoway, 1978). Hence crop rotations that frequently maintain a large proportion of standing cover are potentially less erodible than those where stubble is tilled.

2.5.2.3 Mechanical redistribution

Tillage promotes mixing and movement of soil (Kouwenhoven and Terpstra, 1979). Sweep-type tillage implements move soil particles in the direction of travel, as much as 14.8 cm per pass (Baranowskii and Sweitochowski, 1967). Increasing tillage speeds from 3 to 9 km $hr^{-1}$ promotes lateral soil displacement with sweep-type implements by 1.5 to 2 times (Vasil'kovskii, 1966). Hence frequent tillage, especially in the same direction, will promote the redistribution of topsoil and infilling of topographical features (Kachanoski et al., 1985). Accelerated soil movement from tilled plot areas onto grassed margins and roadways has been observed on experimental areas having well defined boundaries (W. Lindwall; R. Gore, personal communication).

# 3. MATERIALS AND METHODS

## 3.1 Long-term rotation site

The long-term rotations investigated were started in 1958 on the Agriculture Canada Experimental Farm, Indian Head, Sask. Prior to 1958, the site had been uniformly managed in a fallow-wheat or fallow-wheat-wheat rotation. The experimental area is situated on the lacustrine deposits of the Indian Head Association.

Moss and Clayton (1941) classified the area as an Indian Head heavy clay (IHvC), with gently undulating topography and slight evidence of wind erosion. Virgin profiles of this soil were described as having a granular dark brown to greyish black Ah (0 to 15 cm), a cloddy dark brown to blackish transitional $A_2B_1$ horizon (15 to 30 cm) overlying a high lime, massive, grey $B_2$ horizon. The IHvC soils were reported to have sand contents of approximately 6%. Less clayey and more sandy Indian Head Clay soils were often found bordering creeks and other transitional zones between lacustrine and till deposits.

### 3.1.1 Experimental design and original objectives

Originally, ten rotation treatments were implemented to determine the influence of fertilization, fallow frequency, residue management and the inclusion of forage on crop yields and grain protein. One plot, 4.5 m wide and 33.5 m long, was allocated to each rotation-year in a modified Randomized Complete Block Design. For example, a FWW rotation would have three plots allocated per replicate, one for each year in the rotation. This design allowed all stages of the rotations to exist in each year (Zentner et al., 1987).

Rotations were assigned to plots by randomizing 'year groups' within each replicate, then randomizing the rotation treatments within the 'year groups'. A 'year group' contains all rotations which have that year in common. 'Year group-one' contains all rotations, while 'year group-two' contains those rotations having a second year, 'year group-three' contains those rotations having a third year, and so on. Randomization in this manner often resulted in a number of adjacent fallow or crop plots in each replicate.

### 3.1.2 Site management

Cultural practices remained relatively uniform over the length of the study, with only minor changes in fertilizer rates and tillage practices (Zentner et al., 1987). Fertilized rotations received, on average, 6 kg N $ha^{-1}$ and 26 kg $P_2O_5$ $ha^{-1}$ on wheat after fallow, while 39 kg N $ha^{-1}$ and 22 kg $P_2O_5$ $ha^{-1}$ were applied on stubble wheat. Fertilizer was applied based on soil test recommendations after 1978, resulting in higher N and P applications, particularly to stubble wheat. The continuous wheat rotation received slightly more fertilizer than other stubble wheat rotations during this period; however, average application rates were comparable (39 kg N $ha^{-1}$ and 23 kg $P_2O_5$ $ha^{-1}$).

All cropped rotations were tilled in the spring using a heavy duty cultivator. Varieties, seeding rates and equipment are detailed by Zentner et al. (1987). All plots, except those in hay, were tilled in the fall. Forage sod was broken in the fall, prior to the fallow year, using a plow during 1959 to 1969 and a rotovator after 1970. An average of five cultivations were required to control weeds during the fallow period.

Over time, soil accumulated on the edge of the grassed roadway and hindered movement of machinery between replicates. In the spring of 1981, a blade was used to level the shoulders on the grassed roadways. The soil was moved onto the edge of the plot area, and a tilled buffer zone was created (G. Lafond, personal communication).

## 3.2 Preliminary site survey

A survey of the soil variability within the experimental area was carried out in the spring of 1987. Two transects of 50 sites each were sampled. Transect 1 ran east to west through the center of Range 3 (Figure 3.1), with sampling sites at 3.1 meter intervals (lags). Transect 2 began at the south end of the site and ran north (4.6 m lags) through the middle of Plot 24 and across roadways from Range 1 through to 6 (Figure 3.1). Pedological characteristics were described and soil samples were taken.

### 3.2.1 Sampling procedure

A small pit was dug at each site to facilitate description of the soil profile. Characteristics of the soil profile were noted as were anomalies such as plow layer remnants below a 30 cm depth. Depth of the Ap and depth to carbonates were measured at each site.

Soil samples were taken from the Ap and the horizon directly below, either the Ck or Bm horizon. At the sites where the depth of Ap was difficult to determine, samples were taken from the 0 to 15 and 15 to 30 cm depths. Soil samples were air-dried and ground to pass through a 2 mm sieve.

### 3.2.2 Soil analyses

Sand content was determined on the air-dried soil samples, following removal of carbonates and organic matter using 1N HCl and $H_2O_2$ (35%) treatments, respectively. Soil samples were then dispersed by shaking overnight in a sodium hexametaphosphate solution. Sand was collected on a 53µm sieve, dried at 105 °C and weighed.

Total nitrogen was also measured on a finely ground (<100 mesh) subsample from each site along Transect 2. A small amount (50 mg) of sample was combusted under controlled temperature and time steps. The NO gas released was detected by chemiluminescence in the presence of ozone.

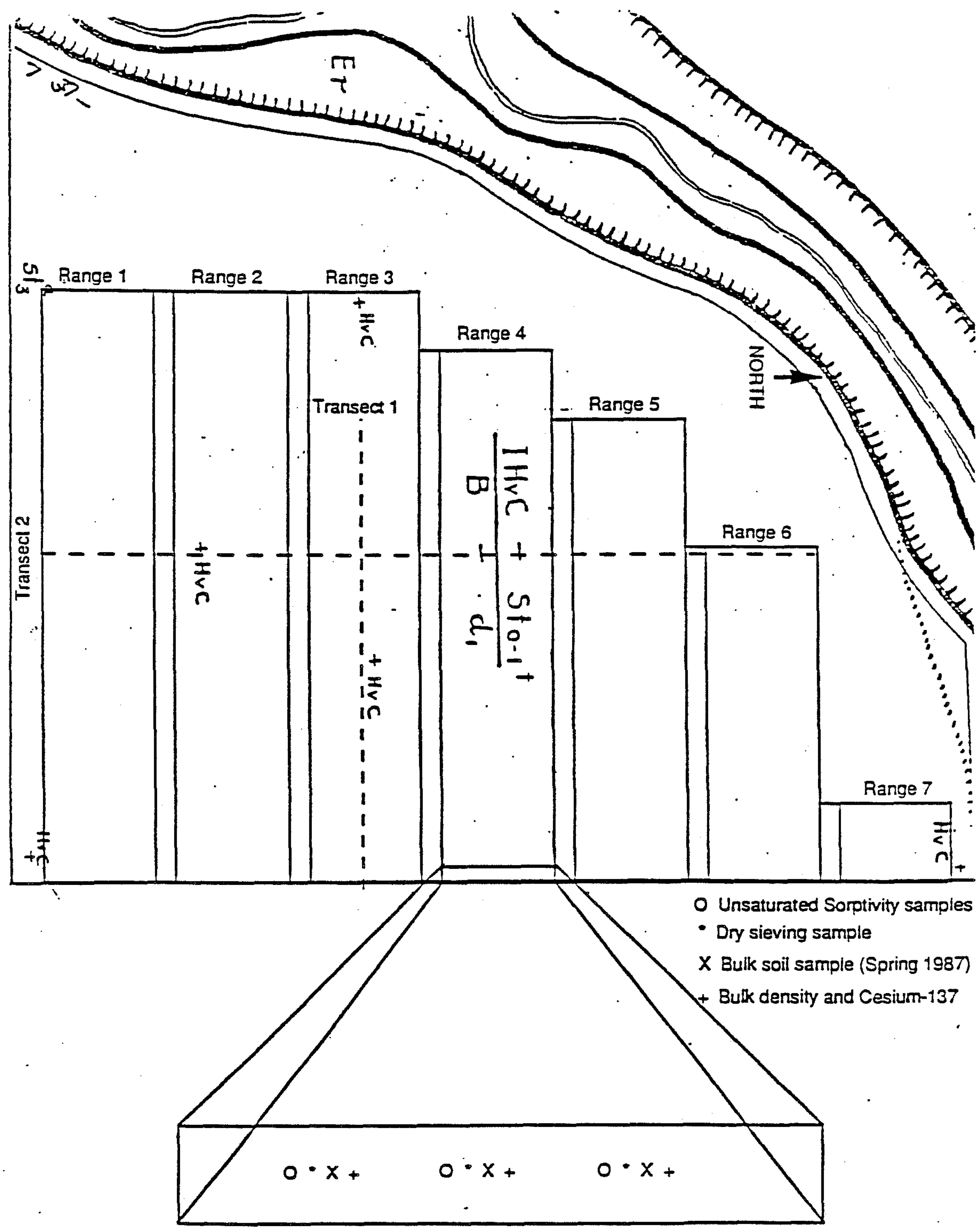



Figure 3.1 Experimental area showing preliminary Transects and sampling locations within plot areas.

† all mapping symbols are described by Moss and Clayton (1941)

### 3.3 Evaluation of soil quality

#### 3.3.1 Rotations selected and phase sampled

Five of the original ten rotations were selected for evaluation of soil quality. These rotations were:

**cont.W**

- Continuous Wheat (N and P added)

**FWW (N+P;+straw)**

- Fallow-Wheat-Wheat (N and P added; straw retained)

**FWW (N+P;-straw)**

- Fallow-Wheat-Wheat (N and P added; straw removed)

**FWWHHH**

- Fallow-Wheat-Wheat-Hay-Hay-Hay (unfertilized)

**FW**

- Fallow-Wheat (unfertilized).

These rotations were selected to evaluate the role of crop residue, brome-alfalfa hay, fallow frequency and fertilization on soil quality. Consideration was also given to the practical use of these rotations throughout the Thin Black soil zone.

Sampling was designed to minimize differences arising from the stage of rotation and evaluate the long-term impact of rotation treatment. Continuous wheat, FWW and FWWHHH rotations were sampled on the plots going into the stubble crop year. Fallow-wheat rotations did not have a stubble crop year, hence samples were taken on plots going into the summerfallow crop year (Table 3.1).

Sampling was restricted to Ranges (replicates) 2, 3 and 4 because of variable soils in Ranges 5 and 6 (Section 4.1). Range 1 was excluded since crop production was noticeably greater than on other ranges, possibly as a result of an adjacent shelterbelt (G. Lafond, personal communication).

Table 3.1 Summary of rotations, cropping phases, depths and replicates sampled over the study.

| Sampling time and Variable measured | PHASE OF ROTATION SAMPLED (as of the year specified) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Unfertilized | | | Fertilized | | | | |
| | FW | FWW | $FW_1W_2HHH$ | $FW_1W_2$ +straw | $FW_1W_2$ -straw | cont. W | DEPTHS* | RANGES |
| **Spring 1987** | | | | | | | | |
| - Mineralization of C, N, and S | W | - | $W_2$ | $W_2$ | $W_2$ | W | all | 2 - 4 |
| - Total C, N, and S | W | - | $W_2$ | $W_2$ | $W_2$ | W | all | 2 - 4 |
| - Densimetric Separation | W | - | $W_2$ | $W_2$ | $W_2$ | W | 0 to 7.5 | 2 - 4 |
| - Aggregate Distribution | W | - | $W_2$ | $W_2$ | $W_2$ | W | all | 2 - 4 |
| - Aggregate Stability | W | - | $W_2$ | $W_2$ | $W_2$ | W | all | 2 - 4 |
| **Fall 1987** | | | | | | | | |
| - Bulk density and Cesium-137 | W | - | $W_2$ | $W_2$ | $W_2$ | W | all | 2 - 4 |
| - Unsaturated Sorptivity | W | - | $W_2$ | $W_2$ | $W_2$ | W | 0 to 7.5 | 1 - 4 |
| - Dry Aggregates | W | - | $W_2$ | $W_2$ | $W_2$ | W | 0 to 7.5 | 2 - 4 |
| - Soil Strength | W | - | $W_1$&$W_2$ | $W_1$&$W_2$ | $W_1$&$W_2$ | W | 0 to 5 | 1 - 4 |
| **Summer 1988** | | | | | | | | |
| - Microbial Biomass C | - | F | F | F | F | - | all | 2 - 4 |
| - Mineral N and S | - | F | F | F | F | - | all | 2 - 4 |
| - Aggregate Stability | - | F | F | F | F | - | all | 2 - 4 |

* sampling included the 0 to 7.5, 7.5 to 15 and 15 to 30 cm depths except where specified.

noticeably greater than on other ranges, possibly as a result of an adjacent shelterbelt (G. Lafond, personal communication).

### 3.3.2 Spring 1987 sampling

#### 3.3.2.1 Sampling procedure

Soil samples were taken from each of the five rotation plots in Ranges 2, 3 and 4 at three locations 8.4 m apart (Figure 3.1). The samples from each replicate were bulked by depth (0 to 7.5 cm, 7.5 to 15 cm and 15 to 30 cm) and stored field moist at 0 °C for laboratory mineralization studies.

Representative subsamples were taken during the set up of the laboratory mineralization study, carefully broken apart (< 8 mm) and allowed to air dry (Kemper and Chepil, 1965). All analyses, other than the mineralization studies, were performed on this air-dried subfraction.

#### 3.3.2.2 Laboratory mineralization of nitrogen and sulfur

Net turnover of N and S was measured using an open incubation system with successive leachings (Stanford and Smith, 1972). A representative subsample was taken from the cold stored, spring 1987 samples and sieved to < 4.75 mm. Approximately 50 g of soil (oven-dry basis) was mixed with 50.0 g of Ottawa sand and placed into plastic incubation-filtration containers (MacKay and Carefoot, 1981). A small piece of glass wool was placed on the surface to minimize soil disturbance during leaching. The samples were incubated at 24 °C for 36 hours to equilibrate microbial activity. Nitrate and sulfate initially present in the soil, were then leached from the samples as described below.

Soil samples were incubated at 25 °C and leached at weeks 1, 3, 6, 9, 12, 15, 18, 21 and 24. Leaching was carried out under suction (300 mm Hg) using 80 mL of 0.001

M $CaCl_2$ solution per sample. Once 80 % of the leachate was recovered, 20 mL of nutrient solution (0.002 M $KH_2PO_4$ and 0.002 M $MgCl_2$ $H_2O$) was added to each sample. Suction was maintained until the glass wool was noticeably dried (2 to 3 hours). Leachates were filter sterilized (0.45 μm) and stored cold until analysis on a Dionex (Model 2110i) liquid ion chromatograph.

3.3.2.3 Laboratory mineralization of carbon

Subsamples were taken from cold storage and prepared as described in section 3.3.2.2, without addition of Ottawa sand. After the initial leaching, a known weight of soil (approx. 50 g oven-dry basis) was transferred to a glass jar with a 0.9 L capacity. Jars were sealed using screw caps and snap lids fitted with rubber septums. These soils were incubated at 25 °C and sampled at 18, 48, 72, 93, 168, 240 and 336 hours. Air samples of 1 $cm^3$ were drawn from the jars and immediately injected into a Fisher-Hamiliton gas partitioner. All jars remained unopened during the study, therefore cumulative $CO_2$ was measured.

The carbon-dioxide peak height of each sample was compared to that of known $CO_2$ standard and the partial pressure of $CO_2$ calculated. Total carbon evolved as $CO_2$ was calculated using the ideal gas law.

3.3.2.4 Routine analysis of carbon, nitrogen, and sulfur

A subsample of air-dried soil was passed through a 2 mm sieve and ground to < 100 mesh. The ground samples were used for determination of total C, N and S as well as inorganic C.

3.3.2.4.1 Carbon in soil and extracts

Total C was determined on ground soil samples using a Leco (Model 600) C-H-N analyzer. Carbon, hydrogen and nitrogen may be measured simultaneously on the combusted sample (950 °C) using infrared absorption (C and H) and thermal conductivity detection (N). Soil organic C content was determined by taking the difference between total C and inorganic C (Tiessen et al., 1983).

Total and inorganic C were measured on leachates and extracts using a Beckman 915B carbon analyzer. A small volume of extract (40 µL) was injected into both the total C and inorganic C reaction tubes. Combustion at 950 $^{o}C$ in the total C reaction tube oxidized all of the C in solution while the lower reaction temperature and phosphoric acid catalyst liberated only carbonate-C in the inorganic reaction tube. Carbon dioxide evolved from each reaction tube was detected using Infra red absorption. Organic carbon was determined by subtracting inorganic carbon from the total carbon.

3.3.2.4.2 Nitrogen in soil and extracts

Total N, excluding nitrates and fixed ammonium, was measured on the finely ground (<100 mesh) sample using a micro-Kjeldahl technique (Bremner and Mulvaney, 1982). Mineral N ($NH_4^+$ and $NO_3^-$) was measured on air dried, sieved (< 2 mm) sample using a 1:5 soil : 2 N KCl extraction and colorimetric determination (Technicon, 1973).

The N content of extracts was determined using the micro-Kjeldahl technique, modified to exclude potassium sulfate amendment during acid digestion of microbial biomass extracts (see section 3.3.4.2).

3.3.2.4.3 Sulfur in soil

Total sulfur was measured on a small, finely ground subsample using a Fisher (model 475) automated S analyzer (Mansfield and Gibboney, 1977).

### 3.3.2.5 Densimetric ('light fraction') separation

Density separations were used to quantify the less dense (<1.6 g $cm^{-3}$), partially humified organic material known as the 'light fraction' (LF) (Spycher et al., 1983). A representative portion of the air-dried surface (0 to 7.5 cm) soils, taken in the spring

1987, were crushed to < 0.66 mm. All organic fragments > 0.66 mm were removed and the soil further ground to < 0.25 mm. Fifteen grams of ground soil was suspended in 60 mL of NaI solution (specific gravity = 1.6 g $cm^{-3}$) and insonated for 3 min at 100 W using a Braun-sonic 1510 ultrasonifier (Spycher et al., 1983; Ladd and Amato, 1980; Dalal and Mayer, 1986d). Suspensions were centrifuged at 2000 g for 30 min to settle the heavy mineral fraction (Greenland and Ford, 1964). Light material floating in the supernatant and adhering to the side of the tube was collected on a 0.45 µm millipore filter and washed (Strickland and Sollins, 1987). The undisturbed soil pellet was then resuspended in 60 mL of fresh NaI using a 1 min insonation, centrifuged and collected as above. Light fractions were washed into a pre-weighed glass scintillation vials, dried for 72 hrs at 60 °C and weighed. Given the low yields of LF, a single determination for C, H and N was done using the Leco (Model 600) C-H-N analyzer (section 3.3.2.4.1).

#### 3.3.2.6 Aggregate size distribution by wet sieving

Approximately 50 g of uncrushed air dried soil (as prepared in section 3.3.2.1) was manually wet sieved to obtain aggregates of the following sizes: > 4.75, 4.75 - 2.00, 2.00 - 1.00, 1.00 - 0.50, 0.50 - 0.25, 0.25 - 0.053 and < 0.053 mm (Elliott, 1986). Samples were placed on the largest sieve, slaked for 5 min in a basin of deionized water and sieved using fifty vertical strokes per min. Soil retained on each sieve was oven dried, weighed and corrected for primary particles. Size distributions were expressed as geometric mean diameter (GMD) as outlined by Kemper and Chepil (1965).

#### 3.3.2.7 Aggregate stability

Aggregates > 0.5 mm and < 2 mm were gently dry sieved from an uncrushed air-dried subsample and stability in water determined. Turbidity of a soil-water suspension, after a period of shaking, was used as an index of the stability of aggregates in water (Molope et al., 1985).

A 0.25 g aliquot of aggregates was weighed onto a quarter sheet of filter paper (Whatman #41) and placed on a porous brick resting in a pan of deionized water. By maintaining the water level about 1 cm below the brick surface, capillary wetting of the aggregates to approximately 55 % (w/w) was achieved in 15 to 20 min. Aggregates were transferred into a spectrophotometer specimen tube and 45 mL of water was added. Samples were shaken end-over-end at 20 rpm for 2 min, removed and settled for approximately 2 min before measuring light transmittance at 625 nm. Samples were shaken a further 20 min, settled as previously described, and transmittance read. The ratio of transmittance (T20:T2) has been used to rank aggregate stability (Williams et al., 1966). However, evaluation of the data suggested that the transmittance after a single shaking of 2 or 20 min would yield more meaningful results (Douglas and Goss, 1982).

Aggregate stability was evaluated over a range of shaking times on the samples collected on June 9/88 (section 3.3.4.1). Stability of aggregates after two min of shaking revealed consistent differences in aggregate stability in the surface (0 - 7.5 cm) soils. More robust aggregates in the 7.5 to 15 and 15 to 30 cm depths required 20 min of shaking.

### 3.3.3 Fall 1987 measurements and sampling

Evaluating soil tilth after a long period of cropping is complicated by the short term influences of tillage and cropping. Soil physical properties were measured after similar cropping phases (Table 3.1), thereby minimizing the short term cultivation influences and providing a useful basis for comparison of long-term crop rotations (Kirkland, 1986).

#### 3.3.3.1. Unsaturated sorptivity

The influence of gravity on infiltration is small over short infiltration times and the uptake of water will approximate the sorptivity of the soil matrix. An unsaturated sorptivity device (USD) was used to restrict water movement through pores greater than 0.75 mm.

The USD used in this study was similar to that described by Green et al. (1986) and Clothier and White (1981). A porous plastic plate (bubble limit of approximately -10 cm water) molded to the bottom of an inverted plastic funnel, formed the base of the USD. A 60 mL syringe with a widened outlet provided a graduated water reservoir when connected to the top of the inverted funnel via nalgene tubing. Suction was maintained by limiting air entry into the enclosed sorptivity device. A 19 gauge needle with an inside diameter of 0.66 mm was inserted through the rubber septum and controlled water flow out of the USD (Clothier and White, 1981).

The inside diameter of the syringe outlet restricted the displacement of water in the reservoir during use. Therefore, a fine wire was hung through the tubing between the reservoir and the USD base to alleviate the bottle neck. Initial filling of the device involved clamping the tubing, disconnecting, filling and replacing the reservoir approximately 3 times. Refilling after each measurement required only clamping the hose and refilling the reservoir.

Field measurements were performed by first inserting a 12.1 cm diameter ring between stubble rows with minimum lateral disturbance and then placing the USD, with the needle inserted, on top of the core. The initial and final times and water levels were recorded and used to calculate sorptivity under suction. Three sorptivity measurements were made at regular locations in each plot (Figure 3.1).

#### 3.3.3.2 Bulk density and cesium-137 concentration

Soil samples were collected from the plots in October, 1987 for determination of bulk density and $^{137}Cs$ concentration (Figure 3.1). Three cores (6.5 cm dia.) were taken from each plot with a hydraulic coring unit. Care was taken to minimize compaction of the core during sampling.

The three soil cores from each plot were divided into 0-7.5, 7.5-15, 15-30 cm segments and bulked by depth. After air drying the samples were weighed, corrected to an oven-dry basis using the hygroscopic moisture contents determined previously, and bulk densities calculated. The soil cores were then crushed to < 2 mm and $^{137}$Cesium concentration determined (de Jong et al., 1982). Uncultivated reference sites, adjacent to the plot area, were also sampled by depth, dried and crushed. The amount of $^{137}Cs$ in the reference soils were used as a baseline to estimate the soil loss (Pennock and de Jong, 1987).

#### 3.3.3.3. Dry aggregate analysis

Erodibility of the plow layer (0 - 7.5 cm) was evaluated using dry sieving (Chepil, 1958). Soil samples were taken as described by Kemper and Chepil (1965), air-dried at 27 $^{o}$C, and rotary sieved. The proportion of aggregates greater than 0.83 mm were measured. Mechanical stability of the dry aggregates was determined by observing the weight loss of the aggregates > 0.83 mm fractions upon re-sieving (Chepil, 1958).

#### 3.3.3.4 Soil strength

Adhesive and cohesive forces in the Ap were evaluated using measurements of tillage draft force. Stubble and summerfallow wheat plots from the selected rotations were tilled (5 cm depth) using an Edwards HD812 Hoe drill (Table 3.1). A detailed description of the implement is given by Collins et al. (1987).

### 3.3.4 Field mineralization study 1988

#### 3.3.4.1 Plot selection and sampling procedures

Rotation treatments were sampled at three times (June 9, July 13 and August 12, 1988) during the fallow period. Plots were selected to evaluate the effects of straw removal, fertilizer and forage cropping on microbial biomass (MB), mineral N accumulation and aggregate stability. Treatments selected for this study varied slightly from those evaluated previously (Table 3.1).

Five soil cores were taken at random from each plot and bulked as 0 to 7.5, 7.5 to 15 and 15 to 30 cm depths. Field moist samples were then stored cold for one to three days before determination of MB-C and -N.

3.3.4.2 Soil microbial biomass

Field moist samples were broken to pass through an 8 mm sieve. Two 50 g subsamples (oven-dry basis) taken and MB-C and N determined using a fumigation - direct extraction technique (Vance et al., 1987; Brookes et al., 1985). Briefly, the procedure involves the extraction of C and N from duplicate subsamples (one $CHCl_3$ fumigated, one control) in 0.5 M $K_2SO_4$. Organic C and N were determined as outlined in section 3.3.2.4 and the amount of MB-C and N calculated using extraction efficiencies of 0.34 and 0.24, respectively (Bremer and Van Kessel, 1989).

3.3.4.3 Aggregate stability

A representative portion of each sample was air dried and sieved to obtain the > 0.5 to < 2 mm size fraction. Turbidimetric aggregate stability was measured as outlined in section 3.3.2.7.

3.3.4.4 Mineral nitrogen

Subsamples were also air dried, ground to < 2 mm and extracted for nitrate and ammonia as described in section 3.3.2.4.2.

## 3.4 Statistical methods

Field replication of the rotation treatments was used to estimate the error terms of all measurements. Hence the error terms contain the variability associated within the measurement technique plus that existing between field replicates (Steele and Torrie, 1980). Estimates of the relative contribution of analytical and subsample variability were performed for turbidimetric aggregate stability and sorptivity measurements to assess degree of replication required to derive sensitive information from these techniques.

ANOVA was used to determine the presence of significant rotation effects. Modification of the ANOVA procedure was required to accomodate time series sampling (section 3.3.4), subsamples (sections 3.3.2.7 and 3.3.3.1) and unequal sample sizes (sections 3.3.3.4) (Little and Hills, 1978; Steele and Torrie, 1980). Least significant differences (LSD) at 5 and 10% probability levels were calculated only after a significant F test ($P \leq 0.05$) was achieved. Significance levels are indicated throughout as: * being $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$ and **** $P \leq 0.0001$.

# 4. RESULTS AND DISCUSSION

## 4.1 Preliminary site survey

Before drawing inferences from any study, some prior knowledge of the background variability is necessary. Large soil variability can obscure or modify the response of soil properties to cultural practices (O'Halloran et al., 1986). Conscientious site selection and the blocking of replicates can increase the precision and validity of the treatment effects measured. Adding replication or altering the experimental design is simply not feasible in the present study since soil quality of the rotation treatments is also a function of time. Therefore, replicates occurring on uniform soil were selected based on the systematic evaluation of soil variability along transects that crossed the experimental area (Figure 3.1).

The Indian Head Experimental Farm is, for the most part, situated on the heavy clay deposits of the Indian Head-Balcarres glacial lake. The Indian Head heavy clay (IHvC) soil type has an A horizon overlying a more strongly structured Bmk or transitional AC horizon, with a strongly calcareous, massive parent material below. Areas where the lacustrine deposits are shallow and modified by inclusions of underlying till are clay and clay loam in texture (Moss and Clayton, 1941). Sand content was used as a simple measure of textural uniformity since the fine, highly sorted lacustrine deposits contain much less sand than the soils modified by the underlying till.

The sand content of the Ap and C horizons along the east-west transect was generally uniform, with only a slight increase in sand content on the western end of the range (Figure 4.1). Sand contents in the Ap horizons were slightly but consistently higher than in the C, except at sites 41 to 50. Slightly higher sand contents in the C horizons suggest that the lacustrine deposits may be thinner on the west side of the site.

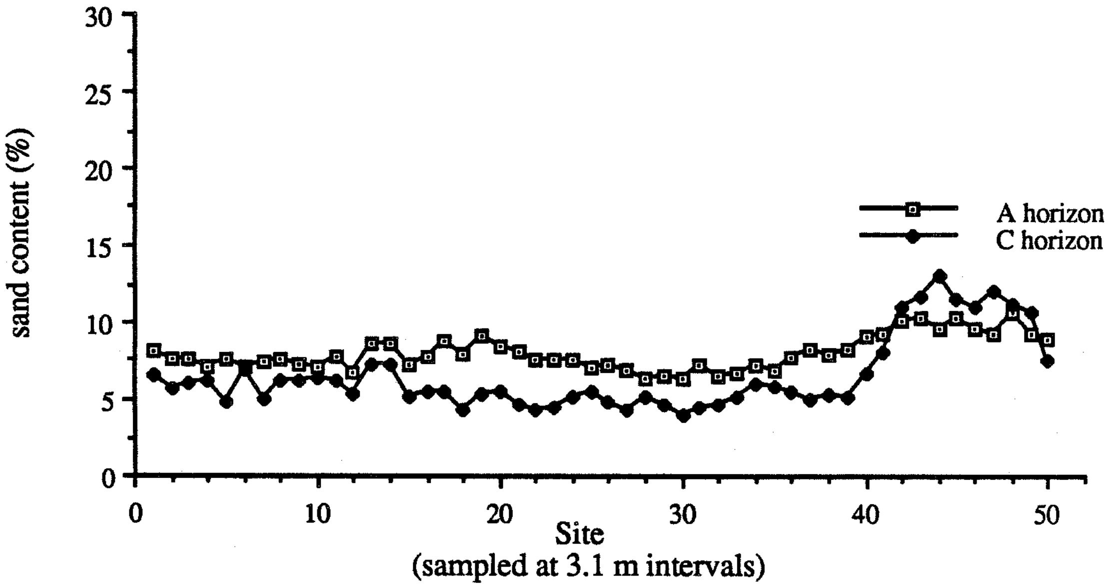



**Figure 4.1 Sand content along the East-West transect through Range 3**

However, the relatively small variation in sand contents (6 to 11 and 4 to 13% in the Ap and C, respectively) indicate a uniform heavy clay texture along the transect.

Sand contents at sites 1 through 35, along the south-north transect (Figure 4.2), were similar to those along the east-west transect.

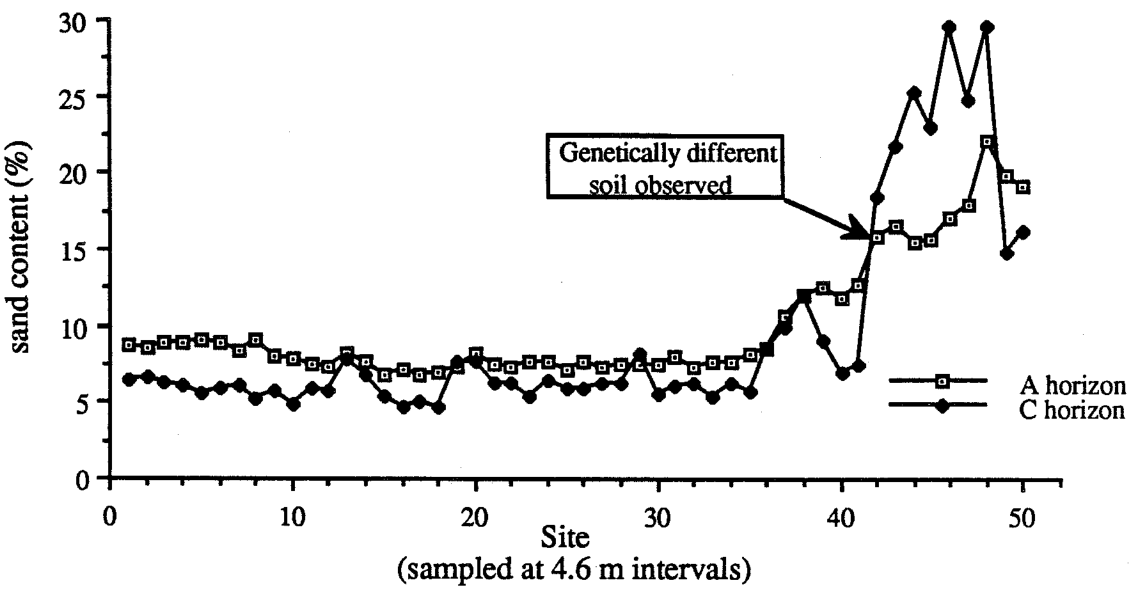



**Figure 4.2 Sand content along the South-North transect**

Lighter textured soils with well developed Bm horizons were noted midway through range 5, consistent with the higher sand contents measured at sites 42 through 50. Thinning of the lacustrine deposits, observed from site 35 to 41, and the presence of a lighter textured Bm horizon suggest that the underlying till influences the soil texture of the northern part of the experimental area, near the creek (Figure 3.1).

Depth of Ap and depth to carbonates (Figures 4.3 and 4.4) lacked a consistent trend from east to west across the experimental area, with the exception of site 1. Site 1 was located on the edge of the grassed border area and had an exceptionally deep Ap (22 cm) and depth to calcium carbonate (30 cm). The deep Ap at this site suggests that less erosion occurred on the grassed border than on the plot areas, or that topsoil eroded from the plots was deposited on the grassed border.

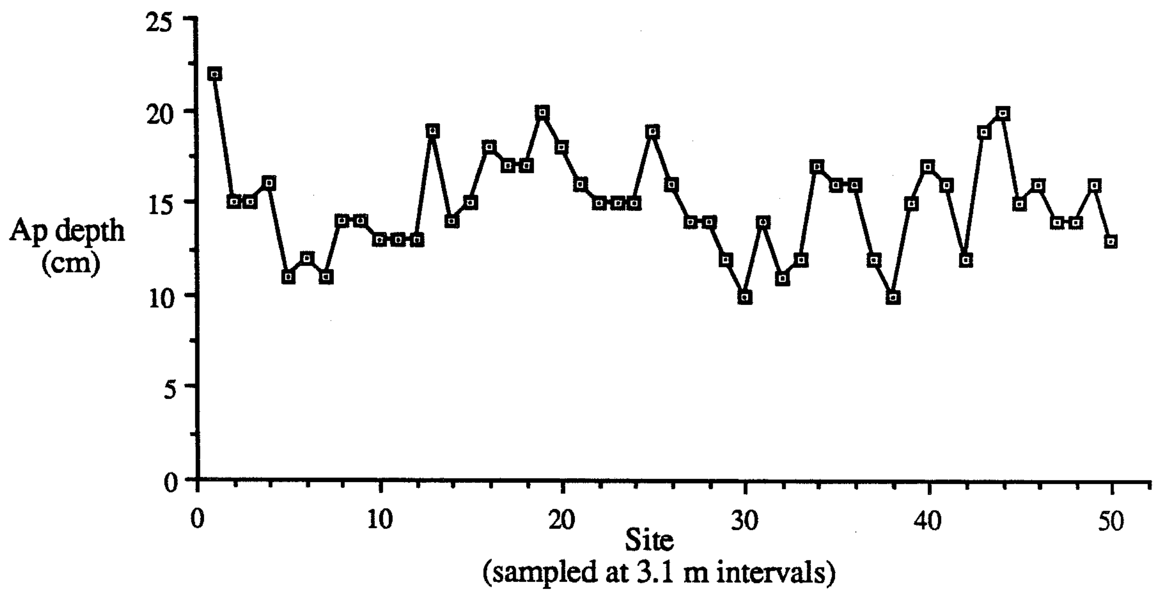



**Figure 4.3 Depth of Ap along the East-West transect**

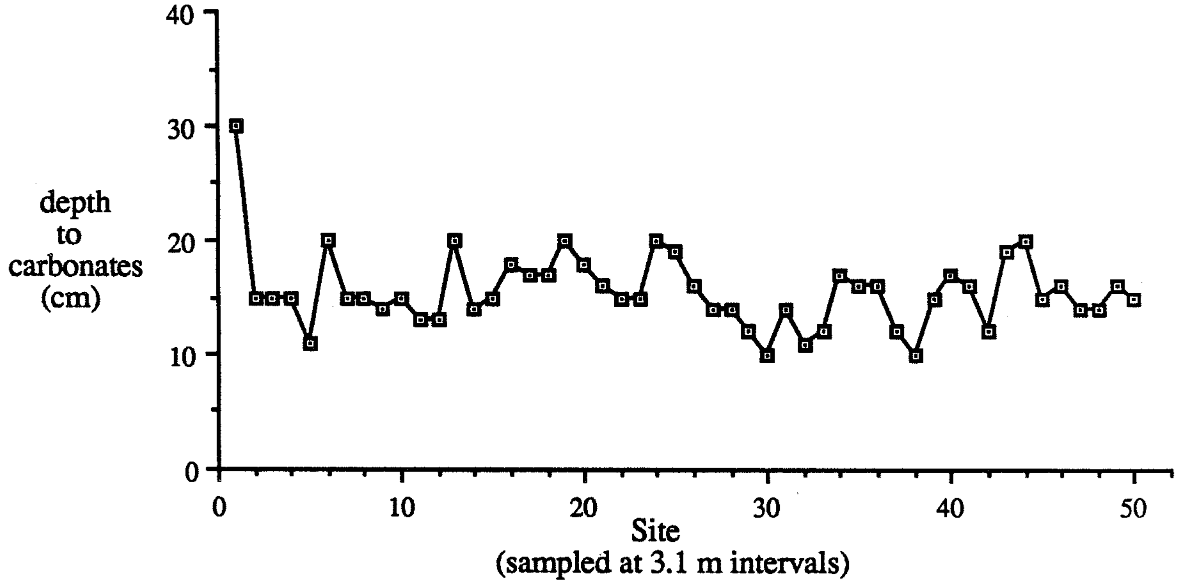



**Figure 4.4 Depth to carbonates along the East-West transect**

Thicker Ap horizons and higher N concentrations were observed at sampling sites located on roadways (Figure 4.5; sites 9, 19, 37 and 46). The mean thickness of Ap horizons was greatest in the FWWHHH rotation (18.3 cm), intermediate in the FWW rotation (15.4 cm) and least in the FW rotation (13.9 cm).

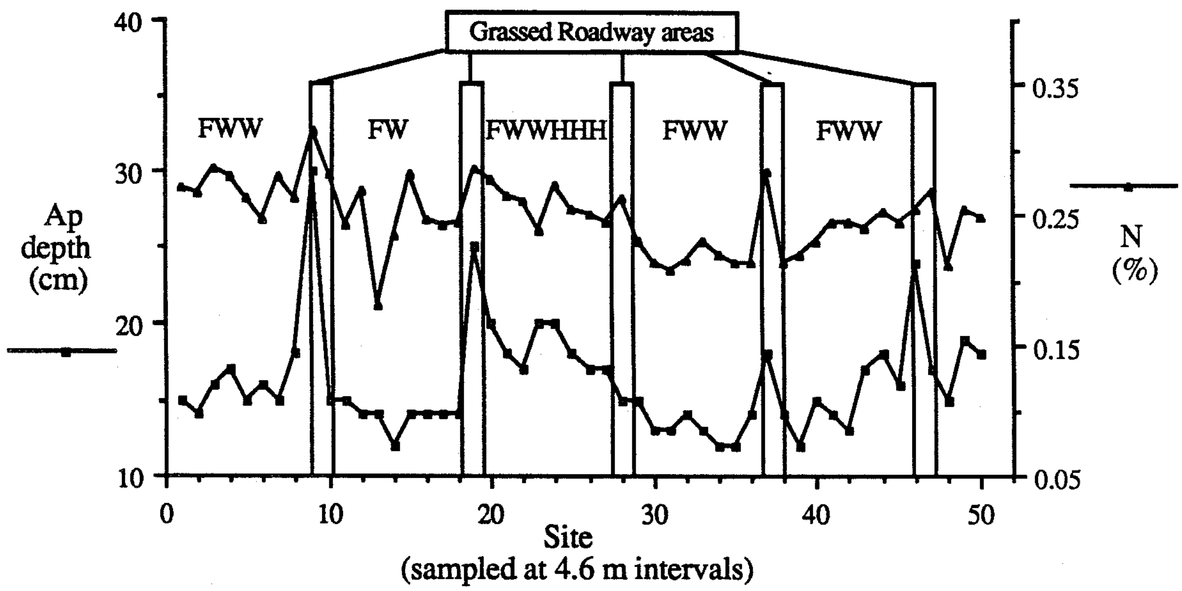



**Figure 4.5 Depth of Ap and N content along the South-North transect**

Some of the topsoil lost from the plots was likely deposited on the roadways, perhaps as a result of tillage and wind erosion (Photographs 4.1 and 4.2). Soil loss from these rotations was further investigated as a mechanism contributing to differences in soil quality.

The depth to carbonates was greater at sites located on the roadways (Figure 4.6), consistent with the accretion of soil that is apparent in Figure 4.5. Sites 42 through 50 had the greatest depths to carbonates, which corresponds with the more sandy soil texture and the well developed profiles. Greater depth to carbonates, lighter soil texture and the presence of a Bm horizon indicate a transition from an Indian Head heavy clay to an Indian Head clay soil at site 42.

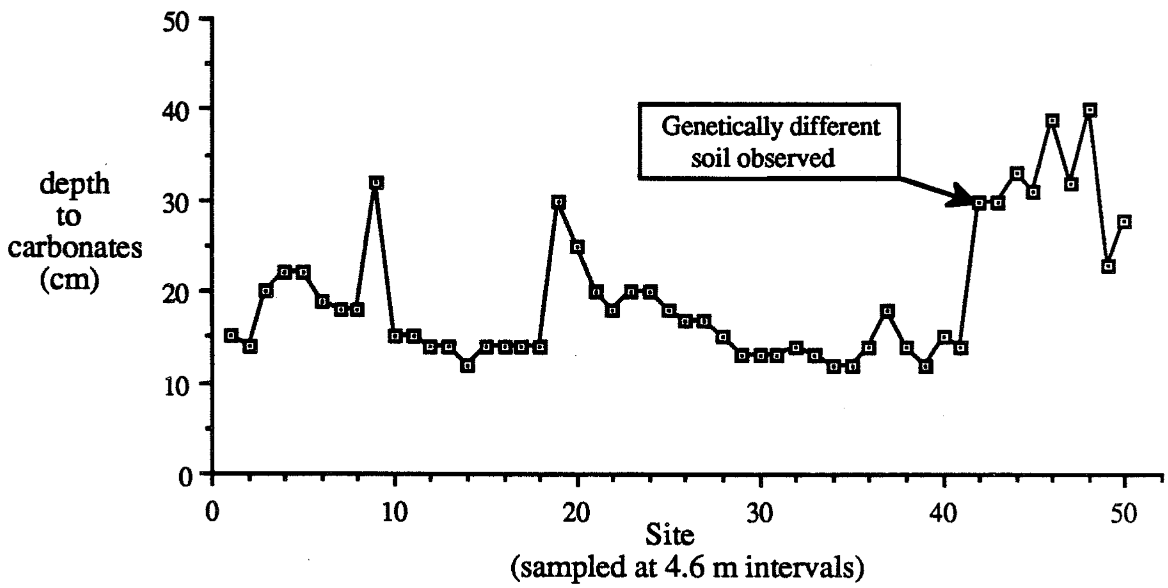
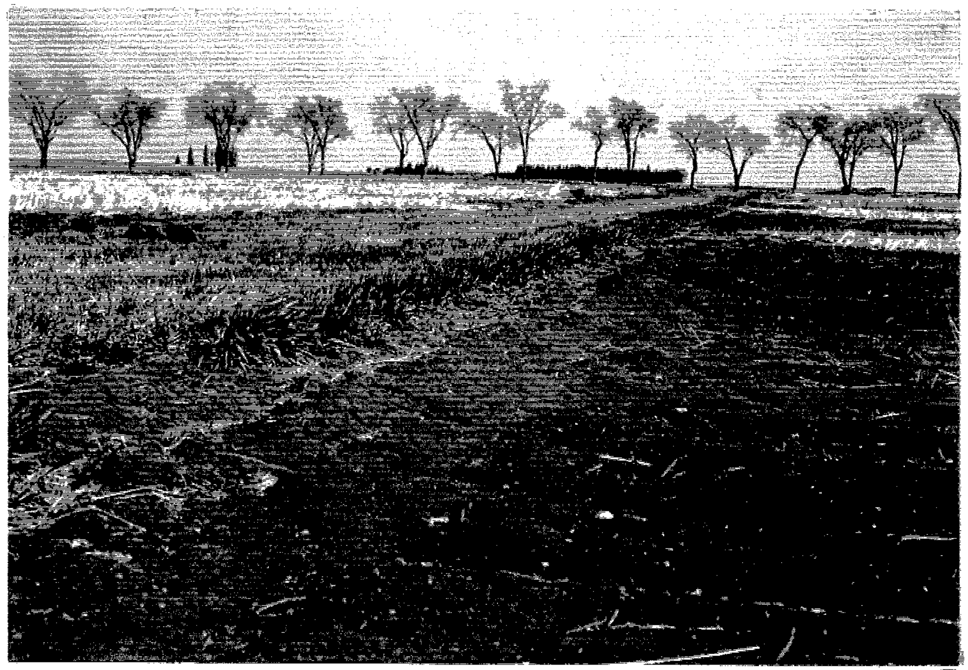
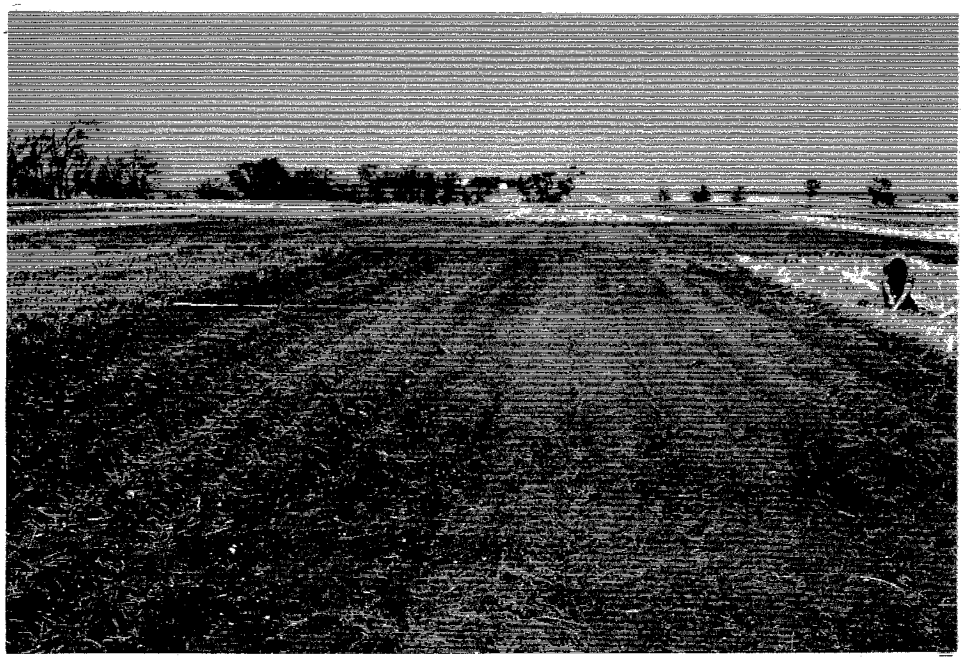



**Figure 4.6 Depth to carbonates along the South-North transect**

Further sampling of rotation treatments was confined to replicates within the IHvC soil type. Replicates in Range 1 were not included in most measurements since previous field experience suggested that the soils in this range were more fertile than other ranges (G. Lafond, personal communication). Range 1 was sampled only when the measurement of highly variable soil properties required additional replication.



Photograph 4.1 Looking eastward at the north end of range 2; soil accumulation is apparent on the edge of the grassed roadway, a probable result of tillage.



Photograph 4.2 A view looking northward midway through range 3, taken in May, 1987. Summerfallowed plots having reduced residue protection often occur adjacent to each other, leaving the soils susceptible to wind erosion.

## 4.2 Impact of crop rotation on soil quality

### 4.2.1 Soil biological properties

#### 4.2.1.1 Organic carbon, nitrogen, and total sulfur

Cultural practices strongly influence the amount of SOM and organically held elements such as C, N and S. The content of these elements reflects the equilibrium of inputs (crop residues) and outputs (mineralization, plant uptake, leaching, volatilization and erosion), provided sufficient time is allowed for the changes in SOM to outweigh the site variability.

The crop rotations that were included in this study differed in the frequency of fallow, number of annual tillage operations and estimated residue additions (Table 4.1). Fallow years were present most often in the FW rotation, followed by the FWW and FWWHHH rotations. An average of five tillage operations was required for adequate weed control on fallow (Zentner et al., 1987). Consequently, rotations frequently in bare fallow had the largest number of tillage passes per year. Continuous W plots were tilled twice per year, since all rotations producing wheat were worked prior to seeding and after harvest. Only wheat stubble underseeded to hay was left untilled after grain harvest.

Residues additions were not measured over the study. However, annual yield can be used to estimate residue additions given the following assumptions:

1). aboveground and belowground dry matter (DM) is proportional to the crop yield

2). the distribution of dry matter above and below ground is not affected by rotation length or fertilization, but is affected by crop type (hay vs. wheat)

3). baling hay or straw removes two thirds of the above ground dry matter (Campbell et al., 1989a).

Table 4.1. Tillage frequency, grain yields and estimated residue additions of crop rotations.

| ROTATION | Proportion of rotation in fallow (yrs) | Tillage over six yr period (tills $6yr^{-1}$) | Mean Grain yield 1960-1984[a] ($kg\ ha^{-1}\ yr^{-1}$) | Estimated residue addition* ($kg\ ha^{-1}\ yr^{-1}$) |
|---|---|---|---|---|
| FW | 0.50 | 21 | 1120 | 2671 |
| FWW (N+P); + straw | 0.33 | 18 | 1464 | 3492 |
| FWW (N+P); - straw | 0.33 | 18 | 1495 | 2077 |
| FWWHHH | 0.17 | 9 | 1548[†](2320)[+] | 3766 |
| cont. W | 0 | 12 | 1810 | 4317 |

* Assumptions made in order to estimate residue addition

1). Aboveground wheat DM = 1.5 x grain yield (Nuttall et al., 1986)

2). Belowground wheat DM = 0.59 x aboveground DM. (van Veen and Paul, 1981).

3). Baling removes two-thirds of the aboveground DM. (Campbell et al., 1989a)

4). Aboveground hay DM = hay yield x 1.5

5). Belowground hay DM = 0.77 x aboveground hay DM (Bowren et al., 1968).

6). Hay DM as stubble and roots = (aboveground DM - hay yield) + belowground DM.

[a] Mean yields taken from Zentner et al. (1987).

[†] Mean wheat yield over the FWW years of the rotation.

[+] Mean hay yield over HHH years of the rotation.

Annual mean grain yields increased as the fallow frequency decreased and fertilizer additions increased (Zentner et al., 1987). Straw, stubble and root residue additions closely followed grain and forage yields, except where straw was removed by baling.

Organic C and N were maintained at significantly higher levels in the cont.W and FWWHHH rotations than in the FWW (N+P; +straw), FWW (N+P; -straw) and FW rotations (Table 4.2a). Fallowing every second or third year, combined with lower residue additions, depleted organic C in the FW and FWW rotations; while lower N levels were likely caused by less fertilizer addition, leaching of mineralized N, and erosion of N-rich topsoil. Continuous wheat and FWWHHH rotations had higher C concentrations since residue returns were comparatively large and depletion caused by tillage was less. Significantly higher organic N contents are probably a result of less topsoil removal and larger additions of symbiotically fixed and fertilizer N in the FWWHHH and cont.W, respectively.

The FWW rotations contained slightly more C and N than the FW rotation ($P = 0.20$ and $0.12$, respectively). Fallowing one year in three caused less depletion of SOM in the FWW (N+P; +straw) and FWW (N+P; -straw) than in the FW rotation. Fertilization may also contribute to the slightly higher SOM level by enhancing residue production. Twenty-seven years of removing straw by baling did not reduce organic C and N contents, in contrast to the significant SOM losses observed in a long-term Swedish experiment where all surface dry matter was removed (Persson and Mattsson, 1987).

Enhanced decomposition of residues under FWW (N+P;+straw) could cause more $CO_2$ evolution and result in soil organic C levels similar to the soils under FWW (N+P;-straw). However, respiration and microbial biomass measurements do not substantiate this suggestion (see sections 4.2.1.3.5 and 4.2.1.3.6). Twenty-five years of straw removal by burning on a thick Black Chernozem has similarly revealed little affect on the soil organic C concentrations (Nuttall et al., 1986).

Table 4.2a. Organic carbon, nitrogen and total sulfur in the 0 to 7.5 cm depth.

| ROTATION | organic C (%) | organic N (%) | total S (%) | C:N:S |
|---|---|---|---|---|
| FW | 1.99 | 0.189 | 0.029 | 69 : 6.6 : 1 |
| FWW (N+P); + straw | 2.14 | 0.207 | 0.028 | 76 : 7.4 : 1 |
| FWW (N+P); - straw | 2.11 | 0.205 | 0.024 | 89 : 8.7 : 1 |
| FWWHHH | 2.38 | 0.231 | 0.024 | 101 : 9.8 : 1 |
| W cont. | 2.40 | 0.232 | 0.037 | 64 : 6.2 : 1 |
| MEAN | 2.20 | 0.213 | 0.028 | |
| $LSD_{0.05}$* | 0.21 | 0.022 | 0.008 | |
| $LSD_{0.10}$ | 0.17 | 0.018 | 0.007 | |
| %CV | 5.1 | 5.5 | 15.7 | |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

Rotation treatment had no significant effect on organic C or N in the 7.5 to 15 cm and 15 to 30 cm depths (Tables 4.2b and 4.2c). Grain-forage rotations did not have more C or N at depth, contrary to the findings on similar rotations on a Dark Brown Chernozem (Janzen, 1987b).

Surface samples from the cont.W contained 43% more total S than any other rotation (Table 4.2a). The coincidental application of S as ammonium phosphate-sulfate (16-20-0-14) was noted in field records on only one year, 1961. This single application was 16 kg S/ha and does not account for the higher total S in the cont.W.

Rotations that included brome-alfalfa forage consistently ranked lowest in total S over all depths, although the variability among replicates precluded significant differences at accepted confidence levels against type I error (Tables 4.2a, 4.2b and 4.2c). Depletion of soil S was expected in the brome grass-alfalfa rotation. Alfalfa has a higher S requirement than wheat, and a larger proportion of the S taken up is removed in the hay than in the grain.

Carbon to S ratios of the organic matter also reflected the S additions to the soils under cont.W and higher S removal in the soils under FWWHHH (Table 4.2a, b & c). A wide C:N:S ratio in the soils under the FWWHHH rotation is consistent with the proportionately larger removal of S with hay cropping. Rotations where only wheat was harvested maintained a much narrower ratio, except where S was removed as baled straw. The surface soil of the cont.W rotation contained proportionately more S in the SOM (C:N:S ratio 64:6.2:1). This was thought to be a result of comparatively low uptake and removal of S as grain, some addition of S as fertilizer and efficient recycling of S through surface residues.

Table 4.2b. Organic carbon, nitrogen and total sulfur in the 7.5 to 15 cm depth.

| ROTATION | organic C (%) | organic N (%) | total S (%) | C:N:S |
|---|---|---|---|---|
| FW | 1.79 | 0.173 | 0.029 | 62 : 6.0 : 1 |
| FWW (N+P); + straw | 2.12 | 0.196 | 0.029 | 73 : 6.8 : 1 |
| FWW (N+P); - straw | 1.92 | 0.184 | 0.025 | 76 : 7.3 : 1 |
| FWWHHH | 2.04 | 0.193 | 0.024 | 85 : 8.1 : 1 |
| W cont. | 1.91 | 0.185 | 0.034 | 56 : 5.4 : 1 |
| MEAN | 1.96 | 0.186 | 0.027 | |
| $LSD_{0.05}$* | ns | ns | ns | |
| %CV | 9.8 | 10.0 | 19.2 | |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

Table 4.2c. Organic carbon, nitrogen and total sulfur in the 15 to 30 cm depth.

| ROTATION | organic C (%) | organic N (%) | total S (%) | C:N:S |
|---|---|---|---|---|
| FW | 1.65 | 0.144 | 0.028 | 60 : 5.2 : 1 |
| FWW (N+P); + straw | 1.83 | 0.170 | 0.032 | 57 : 5.3 : 1 |
| FWW (N+P); - straw | 1.55 | 0.153 | 0.025 | 62 : 6.1 : 1 |
| FWWHHH | 1.31 | 0.144 | 0.023 | 57 : 6.2 : 1 |
| W cont. | 1.63 | 0.153 | 0.030 | 55 : 5.2 : 1 |
| MEAN | 1.59 | 0.153 | 0.028 | |
| $LSD_{0.05}$* | ns | ns | ns | |
| %CV | 16.0 | 15.5 | 25.8 | |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

4.2.1.2 Light fraction carbon and carbon to hydrogen ratio

The light fraction (LF) of SOM in the Indian Head soils ranged from 511 to 1364 mg $kg^{-1}$ soil (Table 4.3), which was about one-quarter the size of this fraction on a Dark Brown loam soil (Janzen, 1987b). Soil textural differences appear to account for the smaller LF in the Indian Head samples, since clayey soils commonly contain less LF than sandier soils (Ladd and Amato, 1980). However, soil zone may also contribute to the differences in LF yields since soil environments that favor decomposition and humification reduce the level of labile organic matter and LF (Roberts, 1985; Molloy and Spier, 1977). Black soils typically undergo more intense humification than do Dark Brown soils, reducing the proportion of organic matter in the partially humified light fraction (Anderson et al., 1974).

The amount of LF carbon (LF-C) in the soil ranged from 153 to 363 mg C $kg^{-1}$ soil and was significantly affected by rotation management (Table 4.3). Unfertilized FW had the least LF-C, followed by, but not significantly less than, the 3 year FWW rotations. Light fraction C was intermediate in the FWWHHH rotation and greatest in the cont.W rotation. This ranking of rotation treatments agrees with the results obtained from similar studies at Lethbridge (Janzen, 1987b).

Residues are the major source of LF organic matter in soils. Carbon accumulation in the LF of the cont.W rotation is caused by the relatively large annual additions of residue from well fertilized wheat crops and limited decomposition as a result of less tillage (Table 4.1). Forages in the rotation enlarge the LF-C since abundant residues are added during the three forage years. The residual N symbiotically fixed in the forage years increased the wheat yield and residue returned (Zentner et al., 1987). However, a single fallow season in the FWWHHH rotation, appears to have accelerated decomposition and offset some of the benefit of residue input, resulting in significantly less LF-C than in the cont.W.

Table 4.3. Characteristics of the light fraction organic matter in the 0 to 7.5 cm depth

| ROTATION | Light fraction Yield (mg $kg^{-1}$ soil) | Light fraction C (mg $kg^{-1}$ soil) | Light Fraction C:H ratio |
|---|---|---|---|
| FW | 511 | 153 | 11.6 |
| FWW (N+P); + straw | 564 | 187 | 11.0 |
| FWW (N+P); - straw | 610 | 189 | 11.8 |
| FWWHHH | 762 | 257 | 10.2 |
| cont. W | 1364 | 363 | 8.4 |
| $LSD_{0.05}$* | | 91 | 2.1 |
| $LSD_{0.10}$ | | 75 | 1.7 |
| %CV | | 21 | 22 |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

Removing a portion of the straw by baling did not significantly alter the level of LF-C in the three year rotations, suggesting that root residues contribute proportionately more C to the LF than surface residues. Including a fallow season one year in three enhances the decomposition of residues and results in LF-C levels similar to the FW rotation. The low LF-C levels found in the FW rotation are due to lesser amounts of residue added and enhanced mineralization and humification cause by frequent tillage.

The size of the LF will reflect the biological importance of this fraction only when the decomposability or quality is the same. Carbon/hydrogen (w/w) ratios can be used as an indicator of substrate complexity or humification (Anderson et al., 1974). Light fraction having a high C:H ratio has a more complex, humified structure with a larger proportion of aromatic structures, and is more resistant to microbial attack. The strong negative correlation ($r = -0.86$) of carbon mineralization over two weeks and C:H ratios of the LF supports this hypothesis (Figure 4.7).

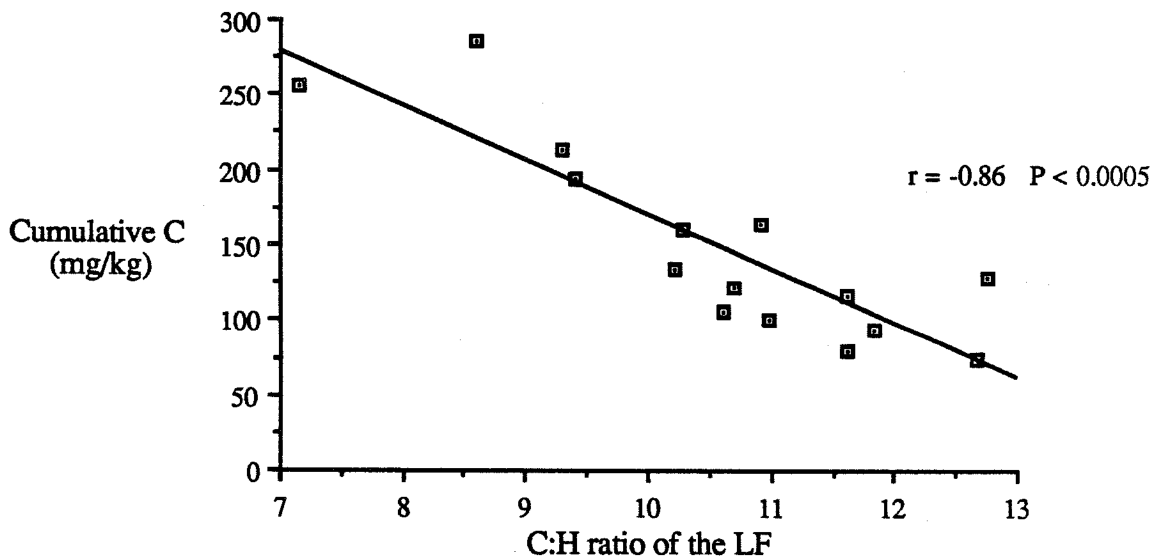



**Figure 4.7 Relationship between cumulative C respired at 336 hrs and the C to H ratio of the LF organic matter**

The rotations with fallow had the highest C:H ratios or least decomposable LF (Table 4.3). Microbial activity is stimulated during the fallow year causing the LF material to be humified to a greater degree. The LF in the cont.W rotation had the lowest C:H as a result of less tillage and less intense conditions for humification. The intermediate C:H ratio in the FWWHHH rotation is likely due to the addition of forage residue three years in six and less frequent fallowing.

#### 4.2.1.3 Carbon, nitrogen, and sulfur mineralization

##### 4.2.1.3.1 Laboratory mineralization of nitrogen

Nitrate-N released from the surface 7.5 cm layer ranged from 80 to 225 mg $kg^{-1}$ soil during a 24 week open incubation (Table 4.4). Surface horizons of an Oxbow association Black Chernozemic soil accumulated similar amounts of N (129 to 246 mg $NO_3^-$-N $kg^{-1}$ soil) over 23 weeks (Roberts, 1985).

Mineralization of N in the surface soils was significantly affected by rotation treatment, with the soils from the cont.W and FWWHHH rotations mineralizing the most N throughout the laboratory incubation (Figure 4.8). Nitrate-N mineralization from the FW rotation was the lowest, while FWW rotations with and without straw baled accumulated similar amounts of nitrate, and were intermediate between the cont.W and FW rotations.

Increased fallowing frequency and the poorer fertilization lowered the soils' ability to supply N. Adequate fertilization and a lack of fallowing appears to be responsible for the improved fertility status in the cont.W rotation. The FWWHHH rotation had a similar mineralization capacity as cont.W, reflecting the net effect of including three years of brome-alfalfa forage and fallowing one year in six. Increasing fallow frequency while maintaining adequate fertility, caused intermediate nitrate turnover in the two FWW rotations. Mineralization and depletion of labile organic N sources during the fallow

Table 4.4. Nitrate-N and sulfate-S mineralized from the 0 to 7.5 cm depth after 24 weeks of incubation at 25 °C.

| ROTATION | Amount mineralized (mg kg$^{-1}$ soil) NO$_3$-N | SO$_4$-S | Proportion mineralized (% of total) N | S |
|---|---|---|---|---|
| FW | 80 | 11 | 4.2 | 3.9 |
| FWW (N+P); + straw | 149 | 17 | 7.2 | 6.0 |
| FWW (N+P); - straw | 135 | 15 | 6.6 | 6.1 |
| FWWHHH | 212 | 21 | 9.2 | 8.7 |
| cont. W | 226 | 21 | 9.7 | 5.8 |
| $LSD_{0.05}$* | 21 | 5 | | |
| $LSD_{0.10}$ | 14 | 4 | | |
| %CV | 6 | 11 | | |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

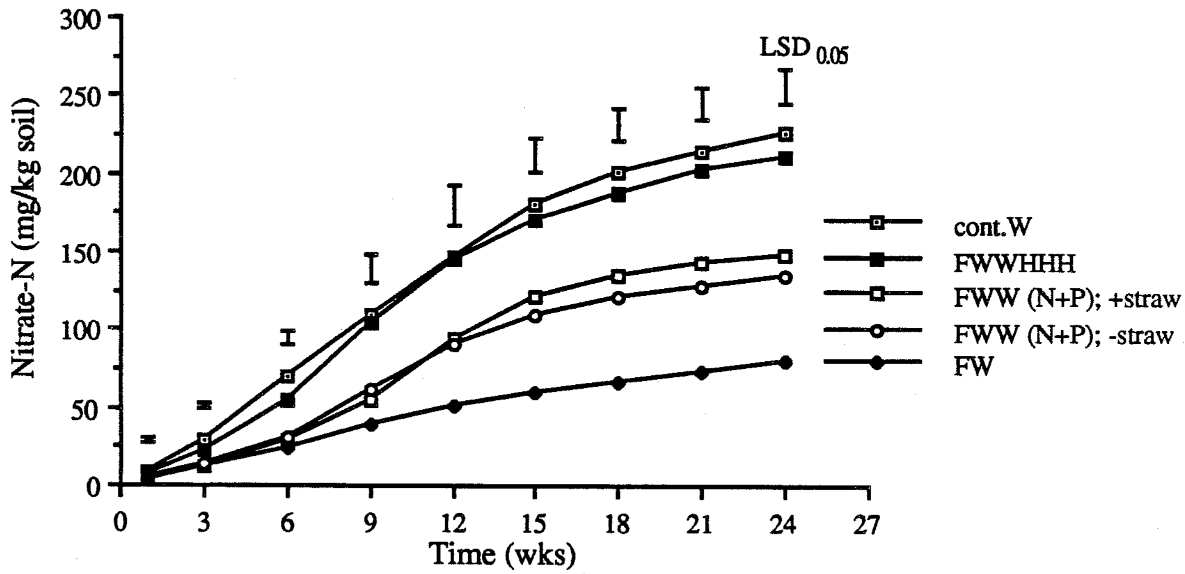



**Figure 4.8 Cumulative N mineralized from the 0 to 7.5 cm depth during a 24 week laboratory incubation at 25 °C**

years could explain the lower N turnover in the FWW as compared to the cont.W or FWWHHH, and in the FW compared to the FWW rotations. However, lack of fertilizer addition to the two year rotation will exacerbate the effect of fallow frequency.

Significant differences ($P \leq 0.10$) in $NO_3^-$-N accumulation in the FW, FWW (N+P; +straw), and FWW (N+P; -straw) rotations (Table 4.4), contrasts with the lack of difference observed in organic C and N contents (Table 4.2a). This dichotomy indicates that stubble cropping, fertilizing and baling straw in FW and FWW rotations may result in statistically similar organic N levels, while strongly influencing the soils' ability to supply N. Hence mineralizable N is more responsive to management than total organic N concentration.

The trend in the proportion of the organic N mineralized to nitrate was similar to that found for net nitrate mineralized across the rotation treatments (Table 4.4). Nine to 10% of the organic N in the soils under cont.W and FWWHHH rotations was mineralized, while the other rotations mineralized from only four to 7% of the organic N. Reduced residues, poorer fertility and frequent fallow resulted in a sequential reduction in the proportion of organic N turned over during the incubation period.

Nitrate-N mineralized from the 7.5 to 15 cm and 15 to 30 cm depths were one-third and one-tenth the amount accumulated in the surface horizon, respectively (Figure 4.8 - 4.10). Subsurface layers in Black Oxbow Association soils released one-third to one-half as much $NO_3^-$-N as the surface horizons during a 16 week incubation (Roberts, 1985).

Differences among rotation treatments were not significant in the subsurface layers (Figures 4.9 and 4.10). Only after long mineralization times (21 and 24 weeks) was the N accumulated in the cont.W and FWWHHH greater than the FW rotation. Few significant differences among rotations indicates that fallow frequency, fertility and residue additions did not have a major effect on the nutrient supplying capacity of

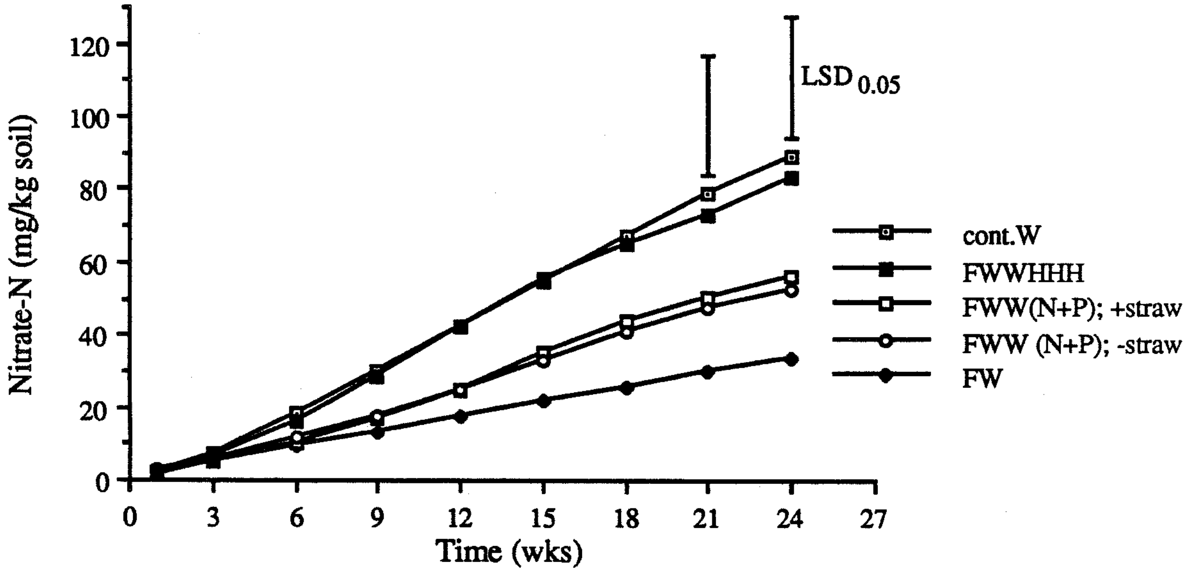



**Figure 4.9 Cumulative N mineralized from the 7.5 to 15 cm depth during a 24 week laboratory incubation at 25 °C**

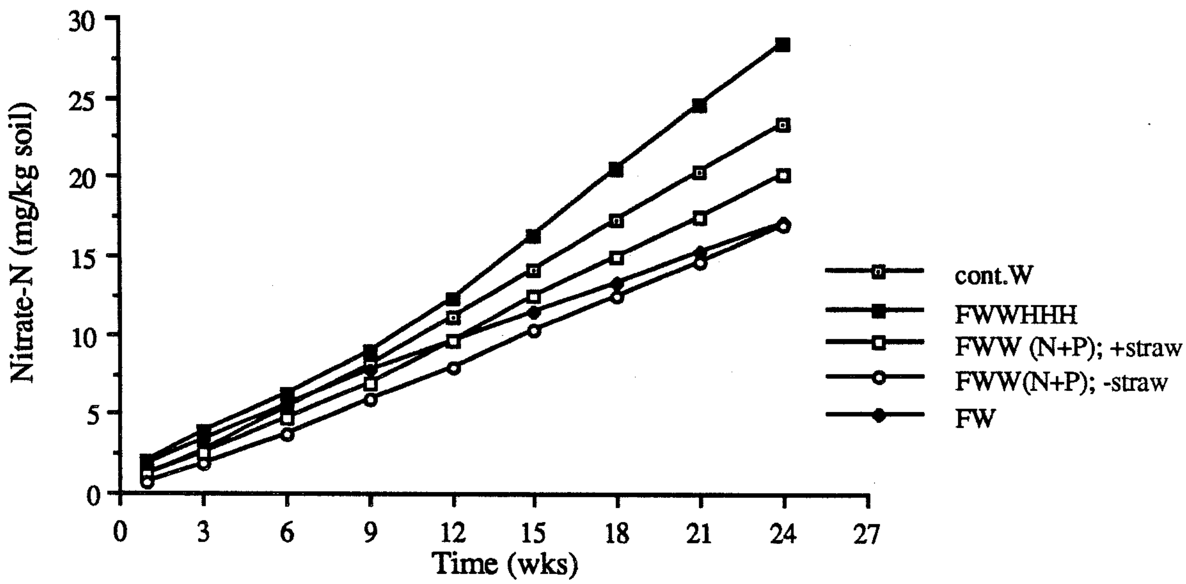



**Figure 4.10 Cumulative N mineralized from the 15 to 30 cm depth during a 24 week laboratory incubation at 25 °C**

subsurface layers. However, the trend in net N mineralized among rotations in the 7.5 to 15 and 15 to 30 cm depths was similar to that found in the 0 to 7.5 cm depth.

4.2.1.3.2 Field mineralization of nitrogen

Large quantities of nitrate and ammonium may build up in soils under bare fallow, as a consequence of the enhanced conditions for microbial oxidation and the absence of plants to take up available N (Campbell, 1978). Rotations were sampled in order to determine the effect of fertilization, straw removal and legumes on N accumulation under field conditions (Section 3.3.4).

Fallow plots in the FWWHHH rotation contained significantly more nitrate and ammonium than all other rotations when sampled on August 12, 1988 (Table 4.5). Breaking and incorporation of the legume residues increased net nitrogen accumulated over the 30 cm profile by 3.2 to 6.0 kg N $ha^{-1}$ in comparison to the other rotations. Mineral N accumulated under fallow were similar in the FWW (N+P; +straw) and FWW (N+P; -straw) rotations, indicating that the amount of residues returned to the soil had little effect on N dynamics. Twenty-seven years of FWW, without fertilizer, significantly reduced N accumulation under fallow ($P \leq 0.10$), confirming that a lack of fertilizer addition may have restricted net N mineralization in the FW rotation during the laboratory incubation. Statistically similar levels of mineral N must be viewed with caution since N may have been mineralized and leached below the 30 cm depth.

Field mineralization of N in the 7.5 to 15 and 15 to 30 cm depths was similar among the fallow plots sampled. This is in agreement with the trends in nitrogen release observed in the laboratory incubation (Figures 4.9 and 4.10).

4.2.1.3.3 Laboratory mineralization of sulfur

Cumulative amounts of S mineralized over 24 weeks ranged from 11 to 22 mg $SO_4^{=}$-S $kg^{-1}$ soil, accounting for 3.9 to 8.7% of the total S (Table 4.4). Roberts (1985) found that 3.6 to 6.4% of the total S was mineralized from a similar soil under comparable incubation conditions.

The cont.W and FWWHHH treatments released the most sulfate over the incubation period (Figure 4.11). Total sulfate accumulation at 24 weeks was lowest in

Table 4.5. Mineral N accumulated over the summer of 1988 in the 0 to 7.5, 7.5 to 15, and 15 to 30 cm depths under field conditions.

| ROTATION | Ammonium- and Nitrate-N (mg kg$^{-1}$ soil) 0 to 7.5 cm | 7.5 to 15 cm | 15 to 30 cm | Available Profile N (kg ha$^{-1}$†) |
|---|---|---|---|---|
| FWW | 13.4 | 12.7 | 11.2 | 41.6 |
| FWW (N+P); + straw | 15.4 | 13.2 | 11.7 | 44.4 |
| FWW (N+P); - straw | 14.8 | 12.5 | 11.2 | 42.5 |
| FWWHHH | 23.2 | 13.1 | 10.4 | 47.6 |
| $LSD_{0.05}$* | 2.4 | ns | ns | |
| $LSD_{0.10}$ | 1.9 | ns | ns | |
| %CV | 7.4 | 6.0 | 7.6 | |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

† mean bulk density of each depth was used to calculate the weight of a hectare furrow slice.

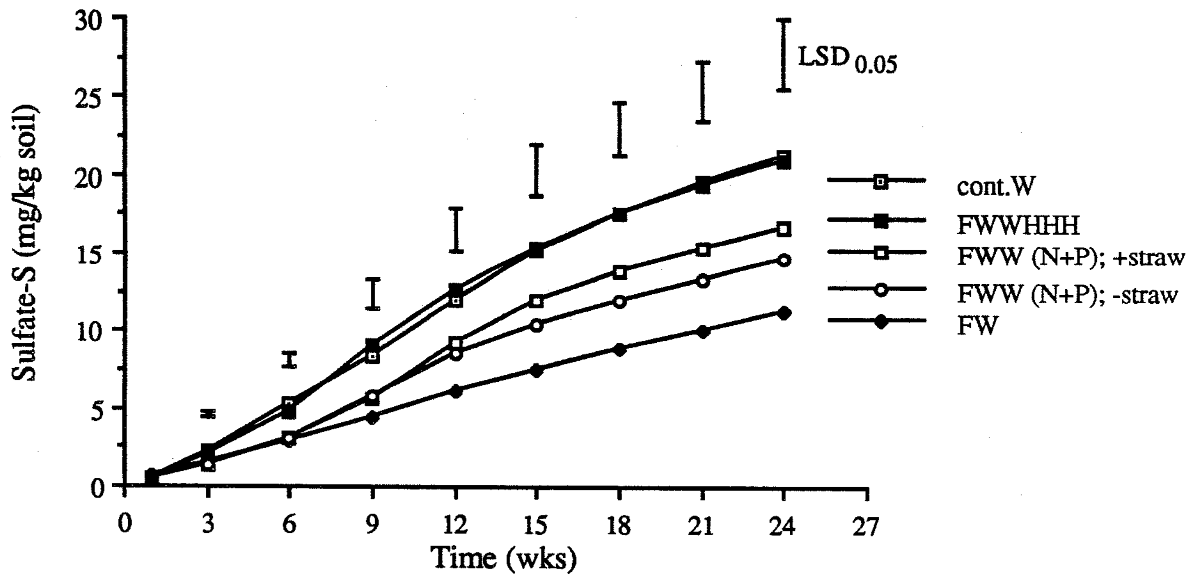



**Figure 4.11 Cumulative S mineralized from the 0 to 7.5 cm depth during a 24 week laboratory incubation at 25 °C**

the FW rotation ($P \leq 0.10$), and intermediate in the FWW rotations (Table 4.4). Straw removal had no impact on the total sulfate accumulated at 24 weeks. The frequency of fallow and amount of residue added did not explain completely the effect of rotation on S mineralization. The coincidental addition of S in some fertilizers and the composition of residues may be other factors influencing S mineralization.

The cont.W and FWWHHH treatments mineralized similar amounts of S, despite significantly more total S present in the soils under cont.W (Table 4.2a), indicating that proportionately more of the total S was labile or mineralizable in the FWWHHH than in the cont.W rotation (Table 4.4). Higher proportions of total S mineralized from Gray soils after ten years of legume cropping, as compared to fallow-wheat cropland, support the hypothesis that legume residues increase the proportion of mineralizable S in the soil (Cowell, 1985).

Soils under cont.W and FWW rotations mineralized similar proportions of the total S originally present, after 24 weeks of incubation, suggesting that the relative amount of labile S was not influenced by fallowing one year in three. In contrast, soils cropped to FW resulted in the least S mineralized (Figure 4.11), despite similar total S concentrations. Bare fallowing every second year, therefore reduces the proportion of mineralizable S (Table 4.4), perhaps by promoting SOM humification.

Subsurface layers (7.5 to 15 and 15 to 30 cm) mineralized only one half and one quarter as much S as the surface 7.5 cm layer, respectively; with rotation generally having no significant effect in the 7.5 to 15 or 15 to 30 cm depths (Figures 4.12 and 4.13). However, after one week, the FWWHHH soil mineralized more S than any other rotation. Continuous wheat released the least S during the first week, while the fallow-wheat rotations were intermediate. Sulfur immobilization by an expanding microbial biomass may be the reason for the small net accumulation of S from the soils in cont.W at week one.

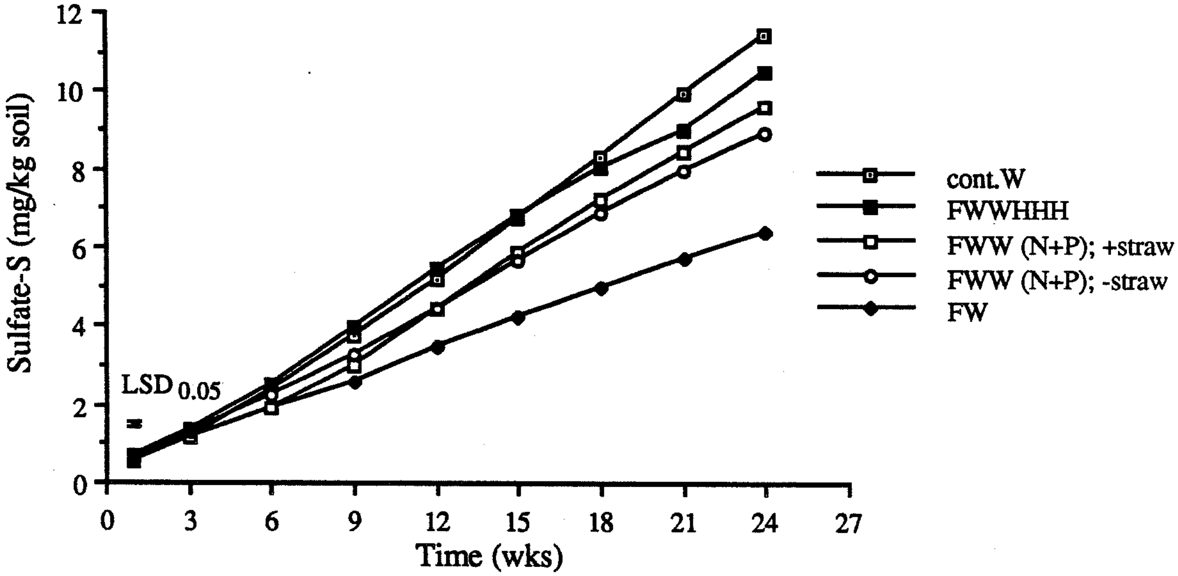



**Figure 4.12 Cumulative S mineralized from the 7.5 to 15 cm depth during a 24 week laboratory incubation at 25 °C**

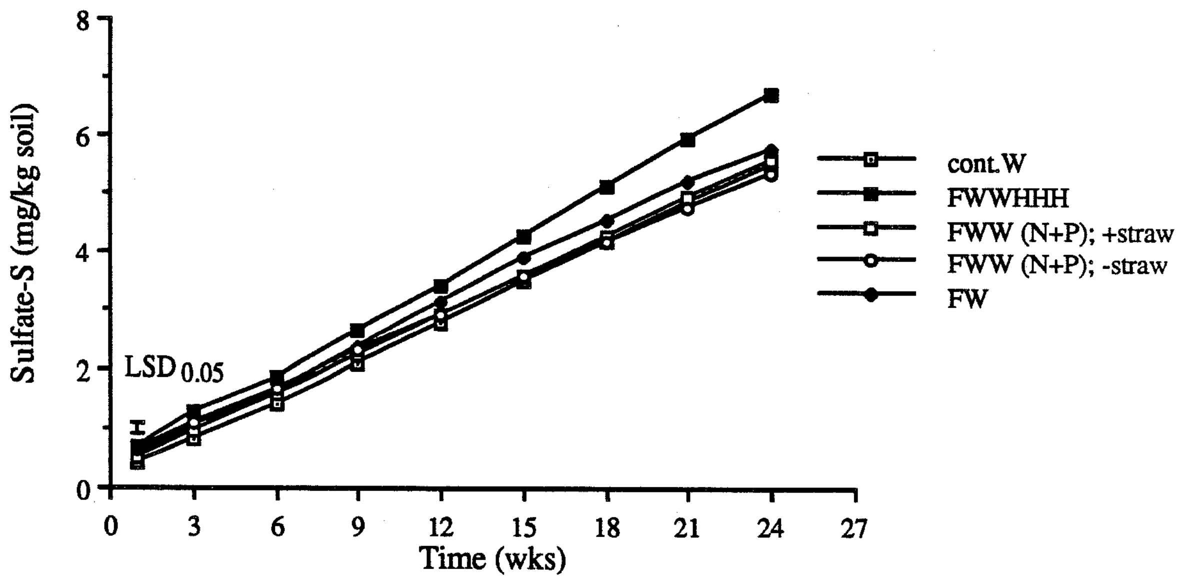



**Figure 4.13 Cumulative S mineralized from the 15 to 30 cm depth during a 24 week laboratory incubation at 25 °C**

#### 4.2.1.3.4 Field mineralization of sulfur

Sulfate accumulation in the field was one-tenth that observed over 24 weeks of laboratory incubation. Fallow plots contained from 6.2 to 7.7 kg $SO_4^{=}$-S $ha^{-1}$ in the top 30 cm on August 12, 1988 (Table 4.6).

Accumulation of S in the 0 to 7.5 cm layer, although small, was significantly affected by rotation. Fallow after legume-grass increased the level of $SO_4^{=}$-S by 0.6 to 0.8 mg $kg^{-1}$. Fertilizer and residue removal did not measurably alter sulfate accumulation. However, the accumulation of $SO_4^{=}$ -S was generally found to decrease across the FWW (N+P;+straw), FWW (N+P;-straw) and FWW rotations.

#### 4.2.1.3.5 Laboratory mineralization of carbon

Carbon respired (mineralized) from the surface soil (0 to 7.5 cm layer) ranged from 86 to 250 mg $CO_2$-C $kg^{-1}$ soil after 14 days of incubation at 25 °C (Figure 4.14). Surface soils from the cont.W rotation respired significantly more $CO_2$ than all other rotations. It is likely that adequate fertilization, larger residue production, and the exclusion of a fallow period result in more mineralizable C. Fallowing one year in six and adding N only as legume residues resulted in less C mineralization than the cont.W, but more than the two or three year fallow-wheat. Soils under FWW respired more $CO_2$ than the FW soils ($P = 0.20$), indicating the effect of fallow frequency and fertilizer additions on SOM.

Mineralization of C in the 7.5 to 15 cm layer was not measurably affected by crop rotation at the $P \leq 0.05$ significance level, except at 48 hours of incubation (Figure 4.15). However, $CO_2$ evolved at all other times was significant at $P \leq 0.10$, excluding the extremely variable 18 and 93 hour sampling times (CVs = 58 and 35%, respectively). After 336 hours of incubation, cont.W and FWWHHH respired more $CO_2$ than the FW or FWW rotations ($P = 0.10$).

Table 4.6. Mean sulfate-S accumulated over the summer of 1988 in the 0 to 7.5, 7.5 to 15 and 15 to 30 cm depths under field conditions.

| ROTATION | Sulfate-S (mg $kg^{-1}$ soil) 0 to 7.5 cm | 7.5 to 15 cm | 15 to 30 cm | Available Profile S (kg $ha^{-1}$†) |
|---|---|---|---|---|
| FWW | 2.0 | 1.8 | 1.7 | 6.2 |
| FWW (N+P); + straw | 2.2 | 2.0 | 1.8 | 6.7 |
| FWW (N+P); - straw | 2.0 | 2.0 | 1.7 | 6.4 |
| FWWHHH | 2.8 | 2.2 | 2.0 | 7.7 |
| $LSD_{0.05}$* | 0.4 | ns | ns | |
| $LSD_{0.10}$ | 0.3 | ns | ns | |
| %CV | 8.3 | 9.3 | 13.1 | |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

† mean bulk density of each depth was used to calculate the weight of a hectare furrow slice.

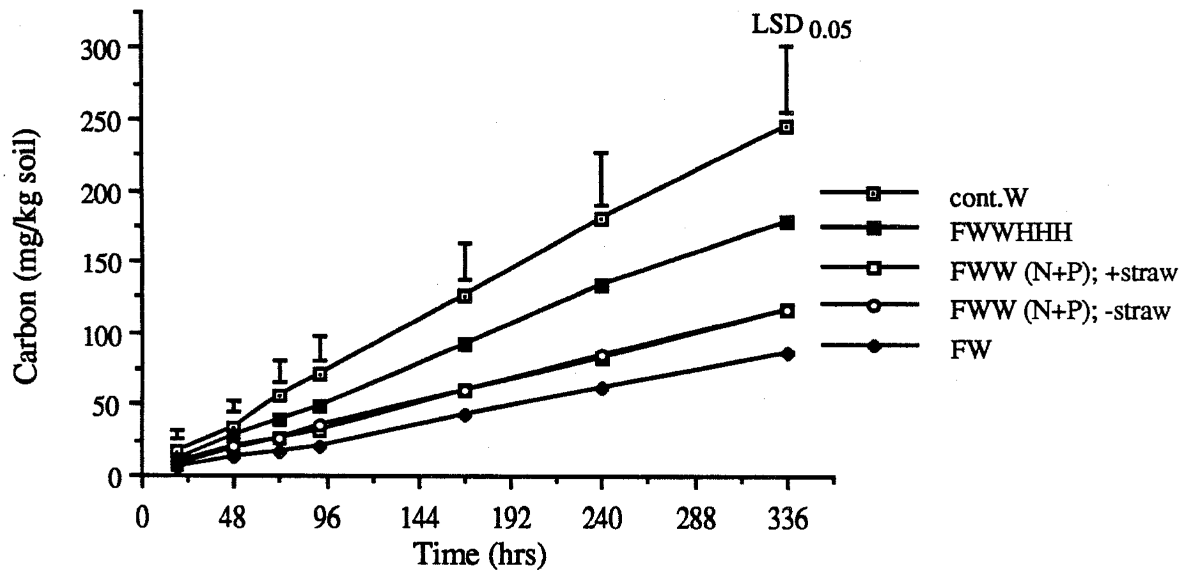



**Figure 4.14 Cumulative C mineralized from the 0 to 7.5 cm depth during a 336 hr laboratory incubation at 25 °C**

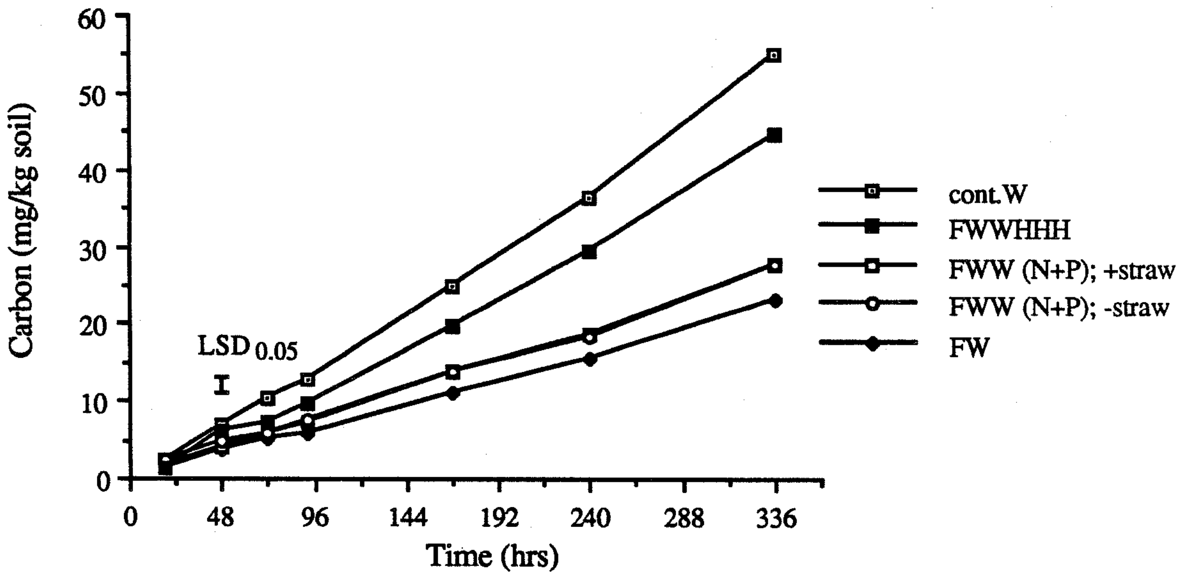



**Figure 4.15 Cumulative C mineralized from the 7.5 to 15 cm depth during a 336 hr laboratory incubation at 25 °C**

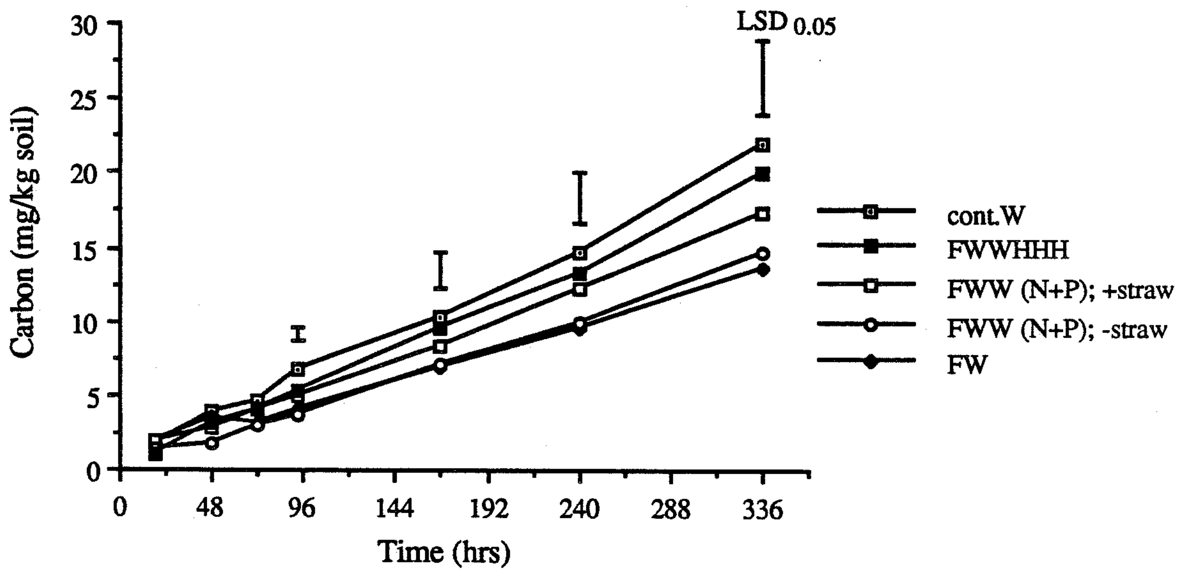



**Figure 4.16 Cumulative C mineralized from the 15 to 30 cm depth during a 336 hr laboratory incubation at 25 °C**

Respiration in the 15 to 30 cm layer was similarly affected by crop rotation ($P = 0.05$), however only at later incubation times (Figure 4.16). Variation in measurements was 23 to 48% of the overall mean during the first 72 hours, while at later times CVs ranged 10 to 15%.

Significant differences ($P \leq 0.10$) in C mineralization among rotation treatments at 7.5 to 15 and 15 to 30 cm depths contrast with the lack of difference found in organic C (Tables 4.2b & c). Readily mineralizable substrates appear to be accumulating at depth in high fertility rotations, possibly by leaching of soluble C or by deposition as roots.

4.2.1.3.6 Field measures of microbial biomass

Direct measurement of the mean microbial biomass size over the summer of 1988 revealed a strong rotation effect. Microbial biomass C in the surface 7.5 cm was highest in the fallow phase of the FWWHHH rotation (Table 4.7). Biomass C levels followed a general trend, with FWW (N+P;+straw) > FWW (N+P;-straw) > unfertilized FWW. This ranking, although not statistically significant, seemed justified given the differences observed in C and N mineralization in the laboratory study.

Microbial biomass in the 7.5 to 15 and 15 to 30 cm depths was higher in the FWWHHH than under the FWW rotations (Table 4.7). Larger quantities of available substrates are likely present in the FWWHHH rotation since C supply by roots is large during forage cropping. A large microbial biomass at depth in the FWWHHH soils is consistent with the higher cumulative respiration observed in the laboratory incubation (Figures 4.15 and 4.16).

4.2.1.4 Relationships between mineralized C, N, and S - Week one

Concomitant mineralization of C, N and S will only occur when the substrate has a C:N:S ratio narrower than the expanding microbial population. Agreement in ranking of C and N mineralized from the surface 7.5 cm suggests that the immobilization of N during the expansion of the biomass was similar across the rotation treatments. Correlation between C and N mineralized was highly significant (Table 4.8).

The amount of sulfate mineralized was not related to microbial respiration or N mineralization at one week (Table 4.8). Immobilization of S by the expanding biomass may have obscured the gross biological mineralization from SOM during the first week.

Table 4.7. Mean microbial biomass carbon measured on fallow plots during the summer of 1988 in the 0 to 7.5, 7.5 to 15 and 15 to 30 cm depths.

| | Microbial Biomass Carbon (mg $kg^{-1}$ soil) | | |
|---|---|---|---|
| ROTATION | 0 to 7.5 cm | 7.5 to 15 cm | 15 to 30 cm |
| FWW | 698 | 483 | 408 |
| FWW (N+P); + straw | 799 | 553 | 410 |
| FWW (N+P); - straw | 743 | 549 | 419 |
| FWWHHH | 1122 | 755 | 589 |
| $LSD_{0.05}$* | 152 | 93 | 92 |
| $LSD_{0.10}$ | 121 | 74 | 73 |
| %CV | 13 | 14 | 17 |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

Table 4.8. Correlations between carbon, nitrogen and sulfur mineralized after one week of incubation at 25 °C.

| | 0 to 7.5 cm | | 7.5 to 15 cm | | 15 to 30 cm | |
|---|---|---|---|---|---|---|
| VARIABLE | $SO_4$-S | $CO_2$-C | $SO_4$-S | $CO_2$-C | $SO_4$-S | $CO_2$-C |
| $NO_3$-N | 0.44 | 0.83** | 0.37 | 0.08 | 0.15 | 0.11 |
| $SO_4$-S | - | 0.20 | - | 0.12 | - | -0.44 |

** significant at $P \leq 0.001$

Alternatively, biochemical mineralization of S may not have been in excess of the amount required by the microorganisms (McGill and Cole, 1981).

Microbial populations in the 7.5 to 30 cm layers of the cont.W and FWWHHH rotations mineralized the most C (Figures 4.15 and 4.16). Nitrate and sulfate mineralization did not coincide with the microbial respiration observed at these depths during week one (Table 4.8). The immobilization of N and S appears to have obscured the differences in gross mineralization expected when the microbial biomass respires and SOM is broken down. An inverse relationship between C respired and S accumulated, significant at the 10.5% probability level, was observed in the 15 to 30 cm depth (Table 4.8). Low S accumulation corresponding with high respiration rates suggests that S was immobilized during the synthesis of microbial biomass.

#### 4.2.1.5 Relationships between organic matter and mineralization

Long term cropping with frequent fallow periods, inadequate fertilization and low residue additions generally accelerates the depletion of organic C, N and LF organic matter in the 0 to 7.5 cm layer (Tables 4.2a and 4.3). Loss of SOM, especially from the biologically active or labile fractions, was closely linked to the decline in N and S supplying power.

Organic C content was directly related to the amount of N and S mineralized at three and 24 weeks (Table 4.9). Correlation coefficients increased from Week 3 to Week 24, suggesting that organic C becomes more important to N and S mineralization over time. Nitrogen concentration was similarly related to N and S mineralization during the study; however, the strength of the relationships was lower than those with organic C. Similar correlations between organic C, N and mineralized nutrients have been reported, although most show a lower degree of statistical significance (Nelson, 1964; Roberts, 1985; Cowell, 1985). Strong associations among N and S mineralized and the concentration of

Table 4.9. Correlation coefficients among selected biological properties and N and S mineralized from the 0 to 7.5 cm depth at 3 and 24 weeks.

| VARIABLE | WEEK 3 $NO_3$-N | WEEK 3 $SO_4$-S | WEEK 24 $NO_3$-N | WEEK 24 $SO_4$-S |
|---|---|---|---|---|
| organic C (%) | 0.84*** | 0.80*** | 0.88*** | 0.88*** |
| organic N (%) | 0.77**** | 0.72**** | 0.81**** | 0.77**** |
| total S (%) | 0.56† | 0.45 | 0.32 | 0.28 |
| Light fraction C ($mg\ kg^{-1}$ soil) | 0.91**** | 0.84**** | 0.81**** | 0.77**** |
| Light fraction C:H ratio | -0.81**** | -0.71*** | -0.75**** | -0.71*** |
| $NO_3$-N week 3 | - | 0.93**** | - | - |
| $NO_3$-N week 24 | - | - | - | 0.95**** |

***, **** significant at $P \leq 0.001$ and $P \leq 0.0001$, respectively.

† - significant at $P \leq 0.05$, although plot reveals two distinct clouds of data points.

organic C and N indicate that supply of N was closely related to S, and both are controlled by the SOM content existing under a given management system.

Total S was not related to S mineralization at three or 24 weeks (Table 4.9). The impact of management practices on the mineralizable S fraction was likely responsible for the lack of relationship between total S and S mineralized. Total S content in the soil under FWWHHH was lower than that of cont.W, yet both mineralized similar amounts of sulfate, probably because the S contained in the FWWHHH soil was present in a more labile humic fraction. In contrast, soil cropped to FW must have a smaller amount of S in labile organic fractions, since sulfate mineralization was much less than other soils with similar total S concentration.

Mineralization at Week 3 was most strongly related to the amount of C in the light fraction (Table 4.9). Rotation treatments having highest residue additions and lowest fallow frequency had the greatest amount of C in the LF and mineralized the most N and S. The amount of LF-C had less impact on N and S mineralization at Week 24, indicating that this fraction becomes less important over time.

Oxidation of the LF seems to drive the mineralization of N and S early in the incubation, while at later times decomposition of other more resistant humic materials will determine the release of N and S. Relationships between organic C and mineralization improved over the incubation period, consistent with the concept that organic C was composed of mainly humic materials that are more resistant to decomposition, but are a slow and consistent source of N and S.

Biological availability of the LF, as indicated by C:H ratio, varied inversely with the amount of N and S mineralized at three and 24 weeks (Table 4.9). Soils containing LF organic matter with narrow C:H ratios are thought to have a greater proportion of simple unassociated humic components, and are able to mineralize more N and S. The C:H ratio of the LF was less strongly related to N and S mineralized at Week 24 than at Week 3.

### 4.2.2 Soil physical properties

#### 4.2.2.1 Distribution of water stable aggregates

The geometric mean diameter (GMD) of aggregates in surface soils (0 to 7.5 cm) was affected by crop rotation (Table 4.10). Mean aggregate size in the soils from cont.W and FWWHHH rotations was about 1.3 times that found in the FW rotation. Increased fallow frequency, baling straw and poor fertilization did not affect the mean aggregate size of the FWW relative to the FW rotation. Studies on the Breton plots in Alberta have also shown that inorganic fertilizers do not improve mean aggregate diameters of soils in FW, while manure additions or hay-cereal cropping increased aggregation by 1.6 times (Toogood and Lynch, 1959).

Mean aggregate diameter determined by wet sieving was closely related to the organic C ($r = 0.64^{**}$, $n = 15$) and LF-C ($r = 0.78^{***}$, $n = 15$) content of the soils. The FWWHHH and cont.W soils probably contained more roots and hyphae which are likely responsible for the larger GMD of these soils (Baldock and Kay, 1987). These temporary binding agents are largely a result of crop growth which is in turn related to soil fertility. Rotations with more organic C and LF-C have larger nutrient supplying capacities, resulting in greater crop growth, more roots and hyphae and, subsequently more and larger aggregates than soils with less organic C and LF-C.

The GMDs of the aggregates from the 7.5 to 15 and 15 to 30 cm depths were less variable than those in the surface soils (Table 4.10). Rotation did not influence aggregate diameter in the 7.5 to 15 cm depth. This was surprising, in that rotations which have greater root biomass (eg. forage and fertilized wheat) are thought to have aggregates of greater diameters (Oades, 1984).

Statistically different aggregate sizes were observed in the 15 to 30 cm depth. Continuous W, FW and FWW (N+P); +straw had the highest GMD, with the FWWHHH having a significantly smaller mean aggregate size (Table 4.10). Moisture

Table 4.10. Geometric mean diameters of wet sieved aggregate distributions from three sampling depths in the spring of 1987.

| | GMD (mm) | | |
|---|---|---|---|
| ROTATION | 0 to 7.5 cm | 7.5 to 15 cm | 15 to 30 cm |
| FW | 0.175 | 0.249 | 0.276 |
| FWW (N+P); + straw | 0.174 | 0.241 | 0.281 |
| FWW (N+P); - straw | 0.171 | 0.222 | 0.250 |
| FWWHHH | 0.221 | 0.230 | 0.245 |
| cont. W | 0.220 | 0.226 | 0.274 |
| $LSD_{0.05}$* | 0.038 | ns | 0.026 |
| %CV | 10.6 | 9.9 | 5.1 |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

content upon drying can alter an aggregate's stability in water and, thereby the size distribution of wet sieved aggregates (Low, 1955). However, analysis using moisture content on drying as a covariant did not explain a significant portion of the difference attributed to rotation treatments (Appendix A). Smaller mean diameters in the FWWHHH rotation were not expected since the greater root biomass that is typical under forage should improve aggregation (Allison, 1968; Oades, 1984).

#### 4.2.2.2 Aggregate stability - Technical evaluation

The amount of water stable aggregates is a useful indicator of the soil's structural stability during water infiltration, since stable aggregates result in a pore system that remains intact and conducts water after wetting. Light transmittance through a shaken suspension of water and aggregates depends on the amount of silt and clay dispersed and is therefore a useful index of water stable aggregation (Molope et al., 1985).

Turbidity of a soil-water suspension will be closely controlled by the settling time prior to reading. If the influence of settling time contributes a large amount to the overall error term then real differences in stability may be masked by the analytical variability.

Subsamples were randomized with respect to order of reading. Reading turbidity commenced after settling approximately 1.5 min and was normally completed within 2.5 to 3 min (18 samples). Error terms attributable to aggregate subsamples plus settling time contributed from 4 to 40% of the overall variability (Appendix C). Shorter shaking periods resulted in less silt and clay dispersed and proportionately more error (40%) associated with the subsample determinations. More fine soil particles were released with longer shaking periods, and relatively less error was caused by settling time.

Shaking disrupts macroaggregates, leaving more stable microaggregates and clay domains intact (Douglas and Goss, 1982). Aggregates from soils under fallow (Table 3.1) were used to determine the level of shaking required to clearly delineate the differences in aggregate stability among soils. In the surface depths the < 2 to > 0.5 mm macroaggregates were weakly stable, dispersing to stable subunits within ten min (Figure 4.17a). Aggregates in the FWWHHH rotation were significantly more stable than the FWW rotations at 2 and 5 min. Aggregates in the 7.5 to 15 and 15 to 30 cm depths were more stable and resisted breakdown until ten or twenty min of shaking had elapsed (Figure 4.17b & c).

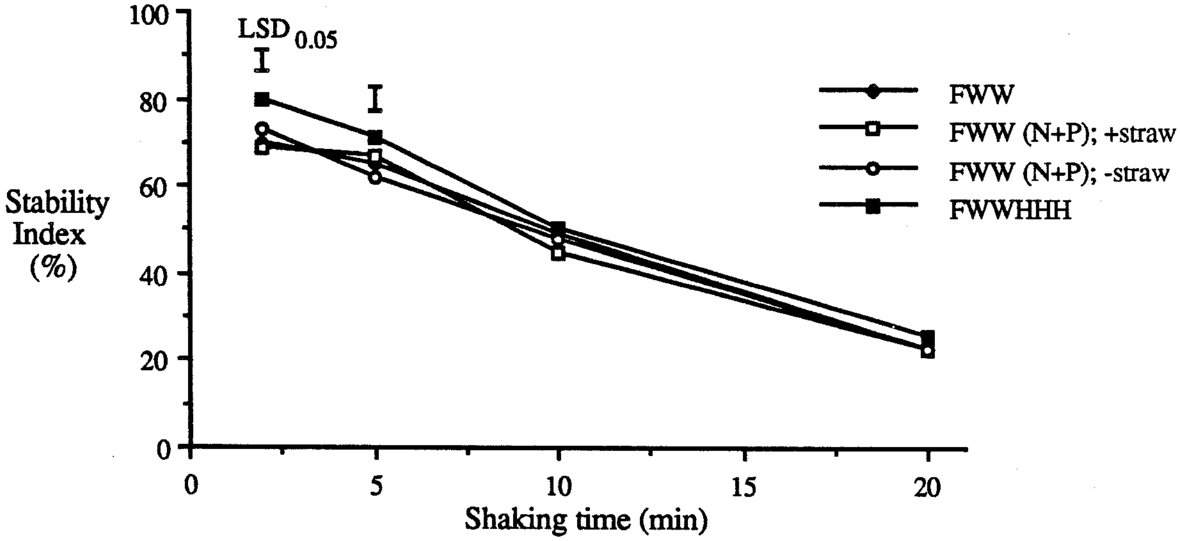



**Figure 4.17a Influence of shaking time on the stability of aggregates in the 0 to 7.5 cm depth**

Turbidimetric aggregate stability can be recommended as a useful technique if: a) the treatment causes aggregate stabilities which are detectable given the variability associated with settling times; b) a shaking time is found which clearly delineates differences in the macroaggregates. Preliminary studies should be conducted to determine the optimum shaking time and the number of samples required to minimize the error associated with settling time, while maintaining a reasonable rate of analysis.

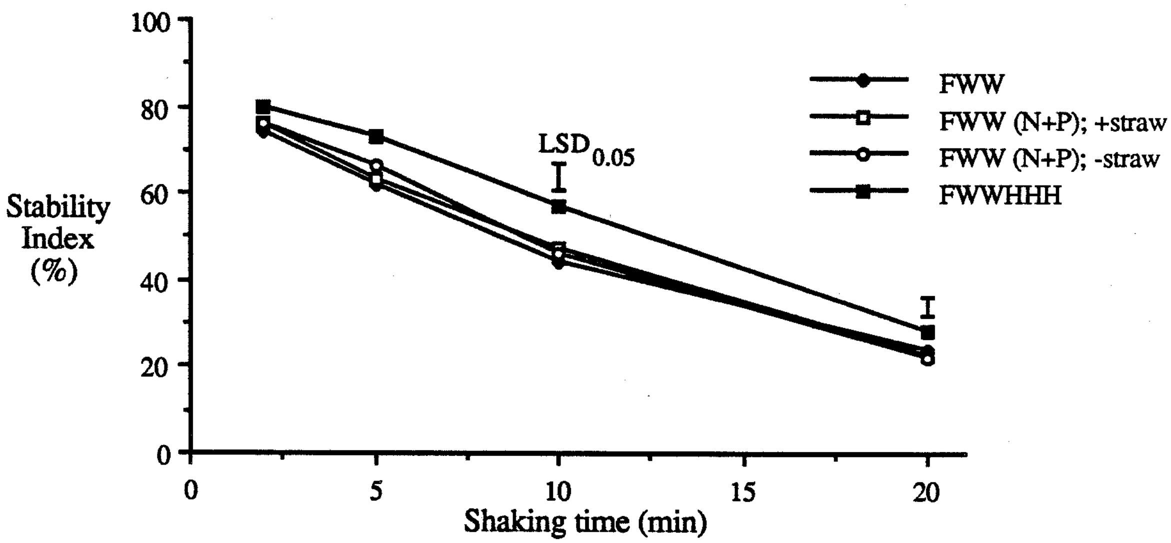



**Figure 4.17b Influence of shaking time on the stability of aggregates in the 7.5 to 15 cm depth**

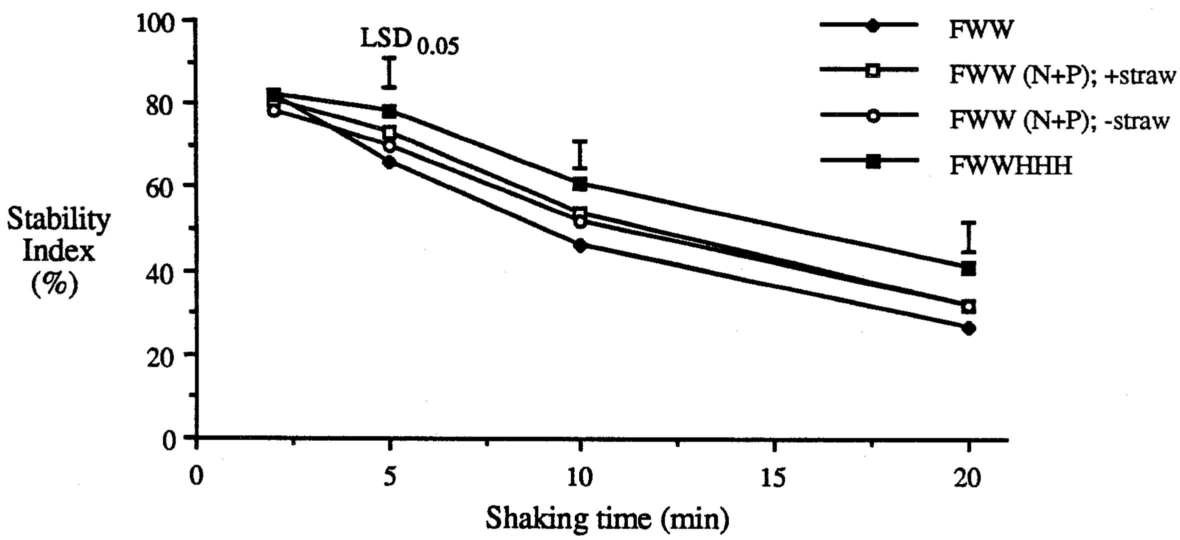



**Figure 4.17c Influence of shaking time on the stability of aggregates in the 15 to 30 cm depth**

4.2.2.3 Aggregate stability - Rotational influences

Rotations influenced aggregate stability only in the 0 to 7.5 cm depth (Table 4.11). Aggregates < 2 and > 0.5 mm were most stable after thirty years of cont.W and least stable after FW. Increased fallow frequency generally resulted in more silt and clay dispersal, higher transmittances and lower aggregate stability. This result is concordant with the aggregate stability of similar rotation treatments on a Dark Brown soil. Dormaar (1983) reported that fallowing significantly lowered the aggregate stability of soils from wheat rotations sampled in the cropped phase.

Including a brome-alfalfa hay three years in six should increase the level of macroaggregation as a result of the fibrous root system and more active microflora associated with a hay crop (Baldock and Kay, 1987; Fraser et al, 1988). Aggregate stability was significantly improved by including hay when sampled directly after the forages (Figure 4.17a, b & c). However, improved aggregate stability within the FWWHHH rotation was less clearly seen when sampled during the stubble wheat year (Table 4.11).

Macroaggregates enmeshed by fibrous roots are short lived, lasting only a few months to a year (Tisdale and Oades, 1983). Such short range improvements in the stability of macroaggregates caused by forage cropping is likely to have little effect during the stubble wheat year of a FWWHHH rotation. Indirect effects of forage cropping on the overall fertility status and rooting density of subsequent wheat crops may cause the slightly higher macroaggregate stabilities, as indicated by the strong positive correlation between LF-C and aggregate stability ($r = 0.79$****, $n = 15$).

Aggregate stabilities were not different among rotations in the 7.5 to 15 and 15 to 30 cm depths when sampled prior to wheat cropping as in the spring of 1987 (Table 4.11).

Table 4.11. Stability of aggregates > 0.5 and < 2 mm in diameter sampled from three depths in the spring of 1987.

| ROTATION | Stability index (%)† 0 to 7.5 cm | 7.5 to 15 cm | 15 to 30 cm |
|---|---|---|---|
| FW | 82 | 29 | 34 |
| FWW (N+P); + straw | 83 | 33 | 37 |
| FWW (N+P); - straw | 85 | 32 | 36 |
| FWWHHH | 87 | 32 | 32 |
| cont. W | 88 | 33 | 32 |
| $LSD_{0.05}$* | 4 | ns | ns |
| $LSD_{0.10}$ | 3 | ns | ns |
| %CV | 5 | 19 | 22 |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

† Stability determined as the percent light transmittance after shaking an aggregate-water suspension 2 min and 20 min for the 0 to 7.5 and the 7.5 to 15 and 15 to 30 cm depths, respectively.

Sampling early in the fallow year, revealed greater aggregate stability in the soils broken out of forage (FWWHHH) as compared to the FWW rotations (Figure 4.17b & c). It is probable that the brome and alfalfa roots enhanced the bonding and stability of aggregates in the subsurface soils, yet these effects do not persist into the stubble wheat crop year.

#### 4.2.2.4 Soil bulk density

Bulk densities of the soils at all three depths were statistically similar under the different crop rotations (Table 4.12). However, crop rotation significantly altered the soil organic matter levels (organic C) and mean aggregate size, both of which affect bulk density (Tables 4.2a and 4.10). Bulk density tended to be lowest under the FWWHHH rotation, and the highest under FW, but small changes in the response variable and an inadequate number of uniform replicates precluded any statistically significant differences.

Density in the surface 7.5 cm followed an expected trend, with rotations containing more organic C having lower densities (Tables 4.12 and 4.2a). This inverse relationship between bulk density and organic C was significant (Figure 4.18), suggesting that a real treatment effect is obscured by variability. If the bulk density measured on cont.W in replicate 4 ({2.28, 1.08} Figure 4.18) is considered an outlier and a missing plot value is calculated using the Least Squares technique (Steele and Torrie, 1980), rotation measurably affected bulk density at $P = 0.12$.

Bulk density in the 7.5 to 15 and 15 to 30 cm depths were higher than in the 0 to 7.5 cm depth but did not differ significantly among rotation treatments. Similarities among densities in these layers were expected since the factors moderating density, organic C and aggregation, were generally not different among treatments.

Table 4.12. Mean bulk density (oven-dry) of rotation treatments at three sampling depths.

| ROTATION | Bulk density ($Mg\ m^{-3}$) 0 to 7.5 cm | 7.5 to 15 cm | 15 to 30 cm |
|---|---|---|---|
| FW | 1.02 | 1.32 | 1.17 |
| FWW (N+P); + straw | 0.93 | 1.25 | 1.16 |
| FWW (N+P); - straw | 0.95 | 1.24 | 1.25 |
| FWWHHH | 0.89 | 1.19 | 1.23 |
| cont. W | 0.95 (0.88)† | 1.24 | 1.20 |
| $LSD_{0.05}$* | ns | ns | ns |
| %CV | 7.9 | 7.2 | 12.4 |
| MEAN | 0.95 | 1.25 | 1.20 |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

† Mean oven dry bulk density of cont. W with outlier removed.

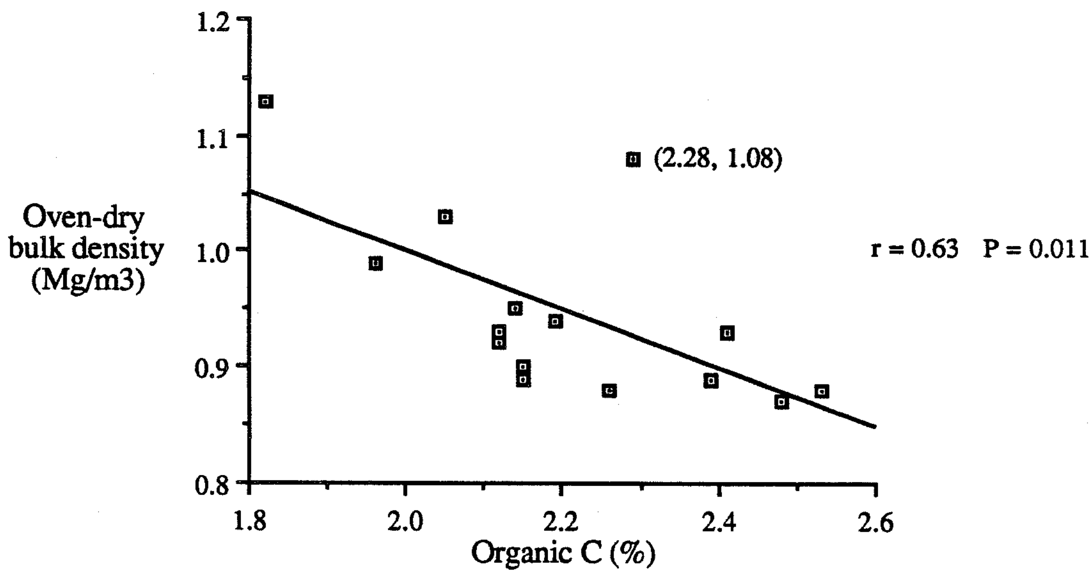



**Figure 4.18 Relationship between oven-dry bulk density and organic C concentration**

4.2.2.5 Unsaturated sorptivity and porosity

Unsaturated sorptivity, or sorptivity measured under a negative head ($S_{neg}$) reflects the ability of the soil to transport water through pores of a diameter less than a given size. Water uptake under a suction of - 40 mm $H_2O$ is directly related to the number of pores < 0.75 mm in effective diameter.

Soil moisture content at the time of measurement also influences sorptivity (Chong and Green, 1983). The moisture content during measurement of $S_{neg}$ in this study was 30.9% and was not significantly affected by rotation (Table 4.13). Hence the $S_{neg}$ determined in this study reflect the differences in soil structure caused by rotation management.

Total porosity, calculated using bulk densities and assuming a particle density of 2.65 g $cm^{-3}$, was statistically similar among rotations. On average the soils contained 64.2% pore space (Table 4.13). Given equivalent total porosities among soils, inferences can be drawn about the relative proportion of pores greater and less than 0.75 mm.

Continuous W cropping resulted in lower $S_{neg}$, while all rotations containing fallow had higher sorptivities (Table 4.13). Lower $S_{neg}$ in the cont.W suggests that a larger proportion of the total pore space is non-conducting macropores, while fallowed rotations, having higher sorptivities, must have fewer macropores and more conducting pores less than 0.75 mm in diameter. Sorptivity on those rotations having a fallow year was not affected by fallow frequency, improved fertility, or straw baling ($P \leq 0.10$). However, the inclusion of forages did reduce $S_{neg}$ and the proportion of pores < 0.75 mm, compared to the FW rotation. Similarities in the $S_{neg}$ and pore space of fallow rotations may be caused by the mechanical disruption of the pore space in the fallow year, which would favor smaller aggregate and pore distributions. Continuous cropping to wheat may reduce $S_{neg}$ and increase the proportion of macropores by promoting frequent

Table 4.13. Unsaturated sorptivity, total porosities and moisture content in the 0 to 7.5 cm depth.

| ROTATION | Sneg ($x10^{-3}$ cm $sec^{-1/2}$) | Total porosity (%) | Moisture content (%) |
|---|---|---|---|
| FW | 30 | 62 | 33.2 |
| FWW (N+P); + straw | 30 | 65 | 31.0 |
| FWW (N+P); - straw | 27 | 64 | 29.0 |
| FWWHHH | 24 | 66 | 28.7 |
| cont. W | 17 | 64 | 32.6 |
| $LSD_{0.05}$* | 7 | ns | ns |
| $LSD_{0.10}$ | 6 | ns | ns |
| %CV | 24 | 4 | 7.8 |
| MEAN | - | 64 | 30.9 |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

drying and cracking of these heavy clay profiles and by improving the system of old root channels often found in relatively undisturbed soil.

Trends in the mean aggregate diameter, LF-C, and organic C were inversely related to sorptivity. Analysis revealed a strong negative correlation between the mean aggregate size and the unsaturated sorptivity ($r = -0.75^{***}$, $n = 15$). Frequently tilled rotations had more small aggregates which resulted in relatively more small pores and a higher $S_{neg}$. Those soils with low $S_{neg}$ values had large GMDs and proportionately more large, non-conducting pores.

#### 4.2.2.6 Soil strength

Draft force required for the first tillage of harvested wheat plots (primary tillage) was used to determine the influence of crop rotation on soil strength (Table 4.14). Soil strength and draft force are affected by soil properties, such as aggregate size and distribution, bulk density, and SOM content. However, other uncontrolled factors such as soil moisture content, stubble and root biomass, and spatial trends in soil texture within the plots may affect draft force to a greater extent than the soil properties influenced by crop rotation (Haines and Keen, 1925b). Soil variability and other confounding factors were present in this study and complicated the interpretation of rotation effects on soil strength.

Mean draft force required for primary cultivation of wheat plots in the FWW (N+P; -straw) rotation was much lower than on the FW or FWW (N+P; +straw) rotations. Continuous wheat and FWWHHH rotations had intermediate draft relative to all other rotations. Confounding effects of soil moisture, soil texture, the amount of straw and root residues may be responsible for the lack of a consistent trend between mean draft force, and soil tilth measured by other methods.

Table 4.14. Draft force required for primary tillage at a working depth of 5 cm.

| ROTATION | Draft force (Newtons) Summerfallow W | Stubble W | Rotation Mean |
|---|---|---|---|
| FW | 233 | - | 233 |
| FWW (N+P); + straw | 242 | 226 | 234 |
| FWW (N+P); - straw | 207 | 232 | 220 |
| FWWHHH | 225 | - | 225 |
| cont. W | - | 230 | 230 |

$LSD_{0.05}$* = 12   CV = 21%

* LSD value applies only to Summerfallow and Stubble W phases and was calculated only after significant difference (P = 0.05) determined by ANOVA.

## 4.3 Impact of crop rotation on erosion and erosion potential

### 4.3.1 Soil loss estimated by cesium-137

Soil loss from the various crop rotations was estimated using $^{137}Cs$ as a tracer. Cesium-137 redistribution was assumed to be solely a function of the cropping treatments, since initiation of the study coincided approximately with the period of peak $^{137}Cs$ deposition (de Jong et al., 1982). The distribution of $^{137}Cs$ and the depth of Ap were assumed to be consistent over the experimental area prior to the study.

All plot areas lost $^{137}Cs$ relative to the reference area that had been seeded to grass in 1958. The surface 0 to 7.5 cm layer lost, on average, 55% of the $^{137}Cs$ present in the grassed reference (Table 4.15). Rotations fallowed every second or third year had the highest relative loss of $^{137}Cs$, while infrequently tilled FWWHHH and cont.W had the least $^{137}Cs$ loss from this layer.

The 7.5 to 15 cm layer contained more $^{137}Cs$ than the reference area, except in the FW rotation (Table 4.15). Tillage should enrich the 7.5 to 15 cm layer in $^{137}Cs$ since tillage, and subsequent soil mixing, was likely deeper than 7.5 cm. Relative depletion of $^{137}Cs$ from the 7.5 to 15 cm layer in the FW rotation suggests that subsoil having a lower $^{137}Cs$ content was mixed into the this layer as soil was lost from the surface.

Estimates of soil loss were based on $^{137}Cs$ contents in the 0 to 15 cm layer, since tillage may move $^{137}Cs$ out of the 0 to 7.5 cm depth and into deeper layers. Weighted $^{137}Cs$ concentration (Bq $m^{-2}$) for the 0 to 15 cm layer was calculated using the bulk density and $^{137}Cs$ concentrations of the individual layers. Soil loss from the 0 to 15 cm (plow) layer was then estimated using the weighted $^{137}Cs$ concentration in the grassed area as a control (Pennock and de Jong, 1987). This calculation did not correct the $^{137}Cs$ concentration of the grassed control site for crop uptake and removal or blowing snow. Use of this correction factor would effectively decrease the soil loss estimates; however, the relative differences among treatments would not change.

Table 4.15. Cesium-137 concentrations and soil loss estimates after 27 yrs under various rotation treatments.

| | Cesium-137 concentration ($Bq\ m^{-2}$) | | Estimated soil loss ($Mg\ ha^{-1}$) |
|---|---|---|---|
| ROTATION | 0 to 7.5 cm | 7.5 to 15 cm | 0 to 15 cm |
| FW | 893 | 230 | 933 |
| FWW (N+P); + straw | 891 | 573 | 655 |
| FWW (N+P); - straw | 923 | 543 | 662 |
| FWWHHH | 1074 | 740 | 409 |
| cont. W | 1065 | 429 | 646 |
| Grassed Reference | 2180 | 285 | - |
| Significance level* (%) | | | 28 |
| %CV | | | 34 |

* Probability that the observed treatment response is a result of experimental error as determined by ANOVA.

Rotation did not have a significant effect on the soil lost from the plow layer, given common levels of confidence against type I error ($P \leq 0.05$). However, other 'randomized' and/or uncontrolled factors such as plot orientation, surrounding cropping treatments, and the occurrence of dry and windy conditions during erosion-prone crop phases will influence the soil loss from any rotation, and result in a high coefficient of variability. Despite these modifying factors, estimated soil losses are caused by chance only 28% of the time (Table 4.15). Conversely, rotation treatment will cause the differences observed in topsoil loss 72 times in 100.

Soil losses from rotation treatments ranged from 409 to 933 t $ha^{-1}$ 27 $yr^{-1}$ or 15 to 36 t $ha^{-1}$ $yr^{-1}$, which agrees with annual erosion rates reported for hummocky terrain in Saskatchewan (Pennock and de Jong, 1987; Kiss et al., 1986). Largest soil losses were estimated on the FW rotation (Table 4.15). Soil loss was lower on the FWW and FWWHHH rotations, suggesting that fallowing less frequently conserved more topsoil. Continuous wheat, although lacking a fallow year, lost almost as much topsoil as the FWW rotations. Soil may have been lost as a result of lateral displacement of soil during spring and fall tillage. Wind erosion during the winter period may have been a factor especially on dry years, when poor crop growth reduces trash coverage and surface protection. Including three consecutive years of hay seems to limit soil erosion and the mechanical displacement of soil by tillage, since the forage crop provides a permanent cover three years in six.

Estimates of soil losses among rotations, although lacking statistical significance, do help to explain the differences observed in depth of Ap along Transects 1 and 2. If soil erosion estimates reflect the relative loss of topsoil, reconstruction of the soil profile by adding topsoil removed to the present day depth of Ap should result in a uniform depth of Ap across the rotations.

Mean depth of Ap for FW, FWW and FWWHHH rotations were determined using observations from Transect 2 (Figures 4.5). Depth of Ap on the cont.W rotation was measured at one site only along transect 1 (Figure 4.3, site 21). Present day (1987) Ap depths are shown graphically in Figure 4.19.

Soil lost over the study can be expressed in mm of topsoil lost from the 0 to 15 cm depth, assuming 1 mm of topsoil weighs 11 t/ha. Reconstruction of the A horizons across the rotation treatments indicates that a uniform Ap, approximately 22 cm deep existed at the start of the study (Figure 4.19). This value is consistent with the depth of Ap observed on the grassed border in transect 1 (Figure 4.3, site 1). Uniformity in the predicted depth of Ap prior to 1960 and the apparent agreement with the thickness of Ap in the grassed area indicates that the estimates of soil loss not only reflect the relative differences in erosion among treatments but accurately determine the quantities of soil lost.

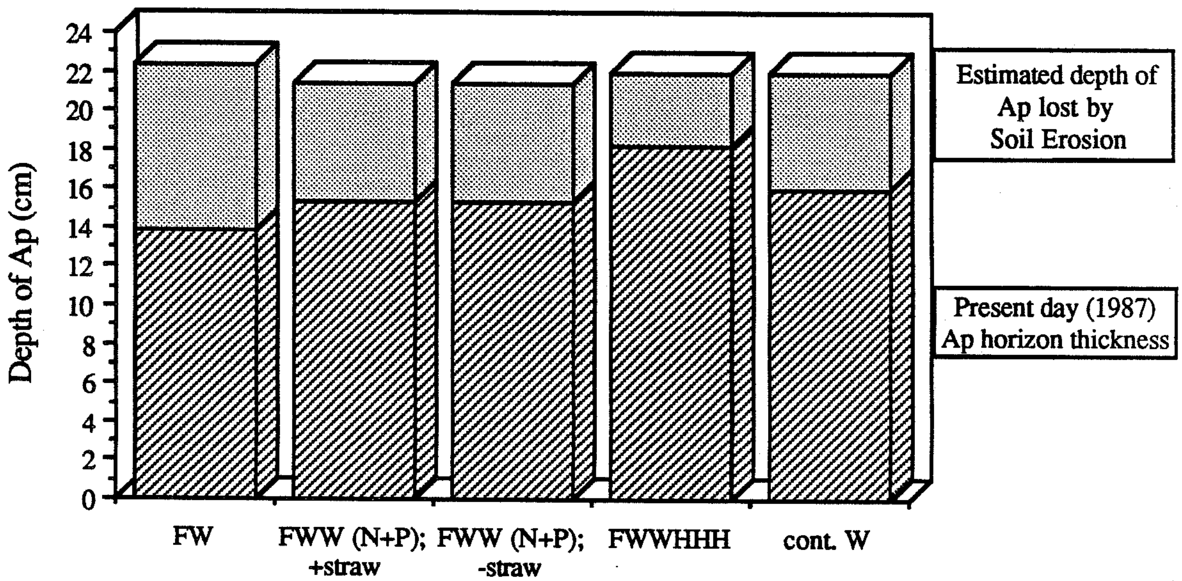



**Figure 4.19 Reconstruction of the mean Ap horizon thickness of the rotation treatments prior to 1958**

4.3.2 Relationship between carbon loss and cesium-137 loss

Losses of topsoil from a site will reduce the organic C concentration by both removing carbon-rich Ap and diluting of the remaining Ap with denser mineral soil from below. Correction for changes in bulk density allows comparison of C losses without the complicating effects of dilution. However, organic C values expressed on a per area basis will be more variable than organic C concentrations (Tiessen et al., 1982).

Cesium-137 concentration in the surface 7.5 cm was closely related to the organic C level (Figure 4.20). Soils having less topsoil erosion or dilution had higher $^{137}Cs$ levels and higher organic C contents. The strength of this relationship implies that organic C content is largely influenced by the amount of soil loss and/or dilution of topsoil with subsoil.

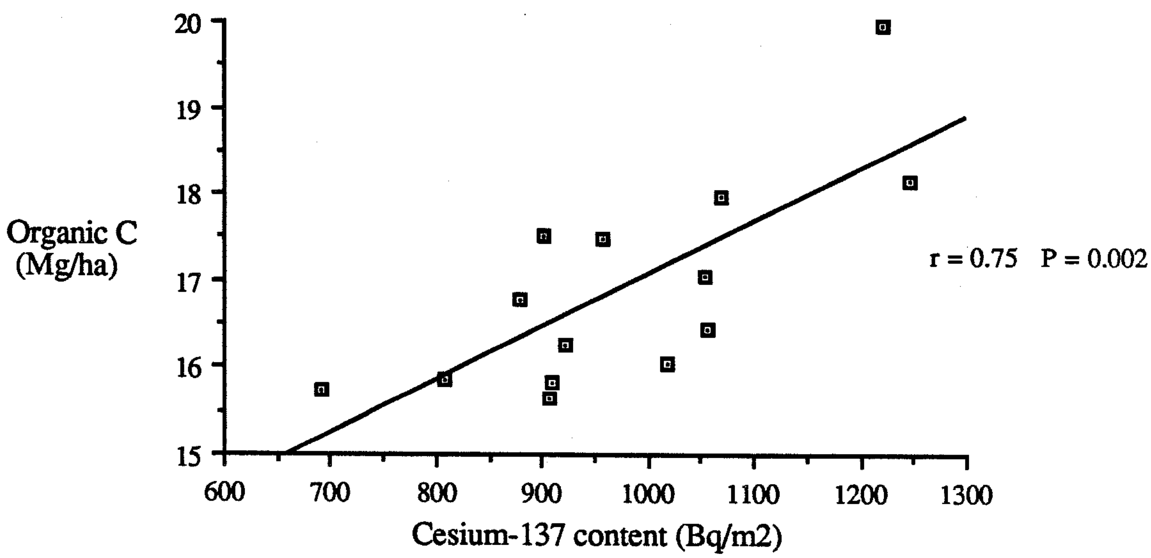



**Figure 4.20 Relationship between organic C and Cesium-137 content in the 0 to 7.5 cm depth**

4.3.3 Wind erosion potential

Crop rotation had a significant effect on the amount and mechanical stability of non-erodible aggregates > 0.83 mm in the surface soils (Table 4.16). Rotations with fallow every second or third year had from 62 to 65% non-erodible aggregates, while less frequently fallowed and continuously cropped rotations contained 70 to 71% erosion resistant aggregates. Therefore, lower wind erosion potential exists in the cont.W and FWWHHH rotations relative to the FW and FWW rotations. This ranking agrees with similar studies where rotations containing continuous cereals generally rank highest in the proportion of non-erodible aggregates (Biederbeck et al., 1984; Mazurak et al., 1953; Armbrust et al., 1982).

Increased erosion protection on the FWWHHH contradicts previous information which reported that legume-grass forage periods increased the erodibility of subsequent wheat plots as compared to a fallow-wheat system (Siddoway, 1963). Improved fertility in the FWWHHH rotation will contribute to greater crop growth causing more roots and fungal hyphae which promote aggregation of non-erodible particles.

Low proportions of non-erodible aggregates in the FW and FWW rotations may be a function of cultivation frequency. Tillage can destroy aggregates and cause a reduction in erosion protection, as compared to untilled or chemically fallowed soils (Armbrust et al., 1982; Nuttall et al., 1986).

Mechanical stability is a measure of the abrasion resistance of non-erodible aggregates. Ranking of the rotation treatments was similar to that observed for the proportion of non-erodible aggregates (Table 4.16). Aggregates from soils under cont.W and FWWHHH were most resistant to breakdown on resieving. Rotations with fallow every third year were significantly less stable, with the FW rotation having the least robust aggregates.

Table 4.16. Indices of soil erodibility potential by wind in the surface 0 to 7.5 cm.

| ROTATION | Non erodible aggregates (% > 0.83 mm) | Mechanical stability (%) |
|---|---|---|
| FW | 62 | 76 |
| FWW (N+P); + straw | 65 | 81 |
| FWW (N+P); - straw | 64 | 81 |
| FWWHHH | 71 | 87 |
| cont. W | 70 | 85 |
| $LSD_{0.05}$* | 5 | 4 |
| $LSD_{0.10}$ | 4 | 3 |
| %CV | 4 | 3 |

* LSD values calculated only after significant difference (P = 0.05) determined by ANOVA.

Potential wind erodibility, based on the proportion and stability of the erosion resistant aggregates, of the rotations can be ranked with cont.W = FWWHHH < FWW (N+P; +straw) = FWW (N+P; -straw) < FW. Continuous W and FWWHHH not only contain more non-erodible aggregates, but these aggregates are more resistant to mechanical breakdown. These improvements in erosion resistance are likely a result of temporary binding agents which influence the formation and persistence of large aggregates.

Both percent non-erodible aggregates and mechanical stability were closely related to the amount of organic C and LF-C in the soil (Table 4.17). Organic C compounds such as polysaccharides, mucilages, and humified components can be directly responsible for gluing soil particles together (Rennie et al., 1954). Improved fertility associated with higher organic and LF-C will enhance aggregation by increasing crop productivity, root growth, exudation, and enmeshing of soil particles (Oades, 1984). Conceptual models of aggregation suggest that the former mechanism is more likely responsible for non-erodible particles > 0.83 mm. However, the role of organic C as a cementing agent must also be considered.

The proportion of non-erodible aggregates was negatively related to estimated soil loss over the study (Figure 4.21). A similar, though statistically weaker ($r = 0.49$, $P = 0.062$), relationship was evident between mechanical stability and soil loss. Larger proportions of non-erodible, stable aggregates will result in a lower erosion potential and, subsequently less soil loss. However, non-erodible aggregates can explain only 45% of the variability in estimated soil loss. Other cultural factors such as the amount of surface residue, degree of standing stubble, coverage on adjacent plots and frequency of fallow years are likely to explain the remaining variability in soil loss estimates.

Table 4.17. Correlations between organic C, light fraction C, and soil erodibility potential by wind in the surface 7.5 cm.

| VARIABLE | Non erodible aggregates (% > 0.83 mm) | Mechanical stability (%) |
|---|---|---|
| organic C | 0.73** | 0.81**** |
| LF-C | 0.65** | 0.72** |

**, ***, and **** indicate significance at $P \leq 0.01$, 0.001, and 0.0001, respectively.

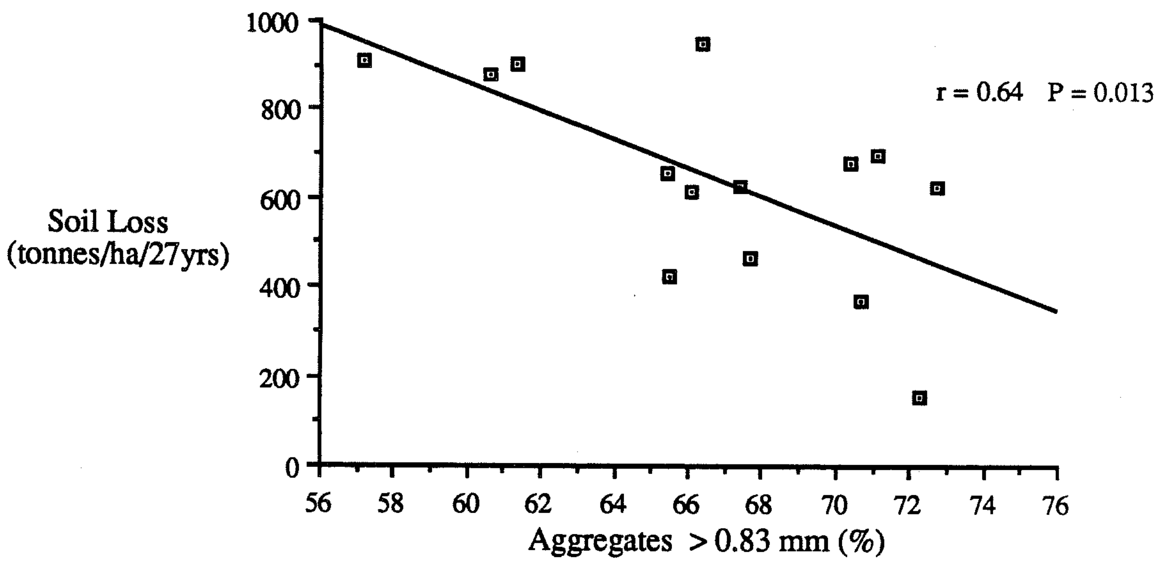



**Figure 4.21 Relationship between estimated soil loss and non-erodible aggregates in the surface layer**

# 5. SUMMARY AND CONCLUSIONS

Systematic transects that crossed the site showed a major change in texture and soil type in the northern part of the experimental area (past Range 4) near the creek bed. Knowledge of the variability in soil type was useful in selecting a uniform sampling area while maintaining as many replicates as possible. Easily observed properties such as depth of Ap and depth to carbonates measured along the south-north transect indicated that topsoil loss and redistribution was an important process within the plot area.

Cont. W and FWWHHH maintained the highest organic C and N concentrations, while baling straw on the FWW rotations had no effect on soil C and N levels. The FW rotation had the least organic C and N, though only slightly below fertilized FWW ($P \leq 0.20$). Total S was similar in all rotations, with the exception of cont. W. Higher total S is only partially explained by additions of S-containing fertilizers in some years. Wide C:N:S ratios emphasize the larger removal of S likely in the FWWHHH and FWW (N+P); -straw rotations, whereas a narrow ratio in cont.W soils is consistent with lower S removed as harvested yield plus some fertilizer addition. Rotation treatment did not alter the organic C, N and total S concentrations in the 7.5 to 15 or 15 to 30 cm depths.

Light fraction is a labile portion of the soil organic matter, and was affected by long-term rotation. Decreasing the fallow frequency, adding fertilizers and including legumes improved the level of LF-C, while baling straw had no significant effect. Frequently fallowed rotations had wider C:H ratios in the LF, indicating that fallowing intensified humification and reduced the decomposability of the LF.

Amounts of mineralizable C, N and S were highest in the fertilized cont. W and unfertilized FWWHHH, intermediate in the FWW rotations, and lowest in the FW rotation. Proportions of these elements mineralized suggested that smaller amounts of the total N were mineralizable in frequently fallowed, poorly fertilized rotations. Retaining straw, fallowing one year in three and providing adequate fertility caused significantly more N mineralization ($P \leq 0.10$) in the soils under FWW (N+P); +straw than soils under FWW (N+P); -straw or FW rotations. Real differences in mineralizable N contrast with similar total N concentrations in the FWW (N+P); +straw, FWW (N+P); -straw and FW rotations, indicating that mineralizable fraction is more sensitive to changes in management than total amounts. Sulfur supply was highest in the FWWHHH and cont. W rotations, with the hay rotation containing proportionally more mineralizable S. Frequent fallowing, less fertilization and lower addition of residues depleted the soils' S supplying capacity. Rotation had no clear effect on N and S supply at depths greater than 7.5 cm. Nitrogen and S mineralization in the field during fallow supported the conclusions drawn from the laboratory incubations. As expected, respiration of C from the 0 to 7.5 cm layer of these soils closely reflected the ranking determined for mineralizable N and S. Carbon mineralization at depths > 7.5 cm indicated that more available C was present under cont.W and FWWHHH, and less under two and three year rotations. This conclusion was supported by field measurements of microbial biomass during the 1988 fallow season.

Mineralization of N and S in the incubation study was strongly related to the concentrations of organic C and N, and LF-C. The LF is a rapidly available source of C for microbial growth and is, thereby, related to the soil's ability to supply N and S. The C:H ratio of the LF and the amount present may be especially useful in determining the mineralizable nutrient capacity of a soil.

Physical properties of the soil were largely a reflection of the SOM levels and associated fertility of the soils. Improved aggregation, especially in the 0 to 7.5 cm layer, was evident going from FW ≤ FWW (N+P); -straw ≤ FWW (N+P); +straw < FWWHHH ≤ cont. W. Higher organic matter, enhanced fertility, and improved fungal and root growth resulted in more macroaggregates. Bulk density lowered throughout this ranking since organic matter and aggregation improved. However, even under FW, the density was $1.02 \pm 0.02$ g $cm^{-3}$, a level not considered to limit root penetration in a heavy clay soil. Inferences about the soil porosity, based on the measurement of sorptivity under negative matric pressure, indicated that the soils under the cont.W and FWWHHH rotations contained less conducting pores (< 0.75 mm) and more large pores, a probable consequence of the larger aggregate distributions. Soil tilth, based on draft force, was difficult to interpret since the measurements were confounded by soil moisture, surface trash and soil variability. Future evaluations of soil tilth using draft force should strive to control the aforementioned factors.

Rotations had differing topsoil losses, with FW > FWW (N+P); -straw ≥ FWW (N+P); +straw ≥ cont. W > FWWHHH. Lack of statistical significance at accepted probabilities against Type I error was expected since the rotation plots were not designed to control other factors affecting erosion. However, reconstruction of the soil profiles estimated a uniform depth of Ap, equal to that of a site seeded to grass since the start of the study. Cesium-137 content explained about 56% of the variability in C levels in the 0 to 7.5 cm layer, indicating that a large amount of the C lost was a result of erosion and dilution of the Ap with subsoil. The amount and mechanical stability of non-erodible aggregates indicated that wind erosion potential followed a ranking similar to fertility status and inverse to the estimated soil loss. Rotations that had sustained larger soil losses (eg. FW) have the lowest fertility, crop growth, trash coverage, and aggregation; all which interact to cause a highly erodible soil condition.

Evaluating soil quality by measuring soil biological and physical properties moderated by SOM, is a useful approach when determining relative differences among long-term cropping treatments. Long-term management altered SOM levels mainly as a result of topsoil erosion, while factors controlling the addition and decomposition of organic residues measurably altered the mineralizable SOM.

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Appendix A. Analysis of GMD in the 15 to 30 cm depth with Moisture Content as a Covariate

| trt | rep | MC | GMD | X trt total | Y trt total | X blk total | Y blk total | total | trt | Blk | ERROR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 18.310 | 0.279 | 57.230 | 0.821 | 109.760 | 1.330 | 5.108 | 46.986 | 145.981 | |
| 1 | 3 | 19.830 | 0.275 | | | 98.920 | 1.361 | 5.453 | 0.000 | 134.630 | |
| 1 | 4 | 19.090 | 0.267 | | | 95.870 | 1.285 | 5.097 | 0.000 | 123.193 | |
| 2 | 2 | 34.310 | 0.292 | 78.160 | 0.829 | | | 10.019 | 64.795 | 0.000 | |
| 2 | 3 | 20.760 | 0.284 | | | | | 5.896 | 0.000 | 0.000 | |
| 2 | 4 | 23.090 | 0.253 | | | | | 5.842 | 0.000 | 0.000 | |
| 3 | 2 | 23.240 | 0.283 | 61.260 | 0.843 | | | 6.577 | 51.642 | 0.000 | |
| 3 | 3 | 20.100 | 0.273 | | | | | 5.487 | 0.000 | 0.000 | |
| 3 | 4 | 17.920 | 0.287 | | | | | 5.143 | 0.000 | 0.000 | |
| 4 | 2 | 19.610 | 0.247 | 54.660 | 0.748 | | | 4.844 | 40.886 | 0.000 | |
| 4 | 3 | 19.680 | 0.264 | | | | | 5.196 | 0.000 | 0.000 | |
| 4 | 4 | 15.370 | 0.237 | | | | | 3.643 | 0.000 | 0.000 | |
| 5 | 2 | 14.290 | 0.229 | 53.240 | 0.735 | | | 3.272 | 39.131 | 0.000 | |
| 5 | 3 | 18.550 | 0.265 | | | | | 4.916 | 0.000 | 0.000 | |
| 5 | 4 | 20.400 | 0.241 | | | | | 4.916 | 0.000 | 0.000 | |
| | | | | GRAND | TOTALS | XY CF | SP for column | 0.683 | 0.421 | 0.035 | 0.227 |
| | | | | 304.550 | 3.976 | 80.726 | | | | | |

| | SSytrt | SSy error | SSx trt | SSx error |
|---|---|---|---|---|
| observed | 0.00331 | 0.00149 | 136.37 | 130.94 |
| corrected | 0.00214 | 0.00109 | | |

**ANOCOVA for Y**

| source | df | SS corr | MS corr | F ratio | Prob >F |
|---|---|---|---|---|---|
| trt | 4.000 | 0.00214 | 0.00053 | 3.425 | 0.080 |
| Error | 7.000 | 0.00109 | 0.00016 | | |

**ANOVA for Regression**

| | | | | | |
|---|---|---|---|---|---|
| Regres | 1.000 | 3.95E-04 | 3.95E-04 | 2.526 | 0.160 |
| Residual | 7.000 | 1.09E-03 | 1.56E-04 | | |

Appendix B.

SORPTIVITY (CM/SEC1/2) REPS 1 THRU 4 — 10:08 THURSDAY, JUNE 30, 1988 1

ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

| CLASS | LEVELS | VALUES |
|---|---|---|
| BLOCK | 4 | 1 2 3 4 |
| TRT | 5 | 1 2 3 4 5 |
| SUBSAMP | 3 | 1 2 3 |

NUMBER OF OBSERVATIONS IN DATA SET = 60

SORPTIVITY (CM/SEC1/2) REPS 1 THRU 4 — 10:08 THURSDAY, JUNE 30, 1988 2

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: SORP

| SOURCE | DF | SUM OF SQUARES | MEAN SQUARE | F VALUE | PR > F | R-SQUARE | C.V. |
|---|---|---|---|---|---|---|---|
| MODEL | 29 | 0.00295838 | 0.00010201 | 2.38 | 0.0104 | 0.697444 | 25.7722 |
| ERROR | 30 | 0.00128336 | 0.00004278 | | ROOT MSE | | SORP MEAN |
| CORRECTED TOTAL | 59 | 0.00424174 | | | 0.00654055 | | 0.02537833 |

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| BLOCK | 3 | 0.00007096 | 0.55 | 0.6502 |
| TRT | 4 | 0.00144232 | 8.43 | 0.0001 |
| BLOCK*TRT | 12 | 0.00087839 | 1.71 | 0.1142 |
| SUBSAMP(TRT) | 10 | 0.00056670 | 1.32 | 0.2625 |

TESTS OF HYPOTHESES USING THE ANOVA MS FOR BLOCK*TRT AS AN ERROR TERM

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| TRT | 4 | 0.00144232 | 4.93 | 0.0139 |

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBSAMP(TRT) AS AN ERROR TERM

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| BLOCK*TRT | 12 | 0.00087839 | $\boxed{1.29}$ | 0.3474 |

Appendix C.1.

TURBIDIMETRIC STABILITIY - CAPILLIARY WET 0 TO 3 DEPTH 16:12 TUESDAY, JUNE 28, 1988 1

ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

| CLASS | LEVELS | VALUES |
|---|---|---|
| BLOCK | 3 | 1 2 3 |
| TRT | 5 | 1 2 3 4 5 |
| SUBSAMP | 3 | 1 2 3 |

NUMBER OF OBSERVATIONS IN DATA SET = 45

TURBIDIMETRIC STABILITIY - CAPILLIARY WET 0 TO 3 DEPTH 16:12 TUESDAY, JUNE 28, 1988 2

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: T2

| SOURCE | DF | SUM OF SQUARES | MEAN SQUARE | F VALUE | PR > F | R-SQUARE | C.V. |
|---|---|---|---|---|---|---|---|
| MODEL | 24 | 374.88888889 | 15.62037037 | 2.97 | 0.0080 | 0.781019 | 2.6971 |
| ERROR | 20 | 105.11111111 | 5.25555556 | | ROOT MSE | | T2 MEAN |
| CORRECTED TOTAL | 44 | 480.00000000 | | | 2.29249985 | | 85.00000000 |

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| BLOCK | 2 | 5.20000000 | 0.49 | 0.6170 |
| TRT | 4 | 194.44444444 | 9.25 | 0.0002 |
| BLOCK*TRT | 8 | 116.35555556 | 2.77 | 0.0309 |
| SUBSAMP(TRT) | 10 | 58.88888889 | 1.12 | 0.3948 |

TESTS OF HYPOTHESES USING THE ANOVA MS FOR BLOCK*TRT AS AN ERROR TERM

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| TRT | 4 | 194.44444444 | 3.34 | 0.0688 |

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBSAMP(TRT) AS AN ERROR TERM

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| BLOCK*TRT | 8 | 116.35555556 | 2.47 | 0.0907 |

Appendix C.2.

TURBIDIMETRIC STABILITIY - CAPILLARY WET 3 TO 6 DEPTH 22:12 TUESDAY, JULY 4, 1989 1

ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

| CLASS | LEVELS | VALUES |
|---|---|---|
| BLOCK | 3 | 1 2 3 |
| TRT | 5 | 1 2 3 4 5 |
| SUBSAMP | 3 | 1 2 3 |

NUMBER OF OBSERVATIONS IN DATA SET = 45

TURBIDIMETRIC STABILITIY - CAPILLARY WET 3 TO 6 DEPTH 22:12 TUESDAY, JULY 4, 1989 2

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: T20

| SOURCE | DF | SUM OF SQUARES | MEAN SQUARE | F VALUE | PR > F | R-SQUARE | C.V. |
|---|---|---|---|---|---|---|---|
| MODEL | 24 | 497.42222222 | 20.72592593 | 6.96 | 0.0001 | 0.893074 | 5.3888 |
| ERROR | 20 | 59.55555556 | 2.97777778 | | ROOT MSE | | T20 MEAN |
| CORRECTED TOTAL | 44 | 556.97777778 | | | 1.72562388 | | 32.02222222 |

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| BLOCK | 2 | 87.24444444 | 14.65 | 0.0001 |
| TRT | 4 | 96.53333333 | 8.10 | 0.0005 |
| BLOCK*TRT | 8 | 297.86666667 | 12.50 | 0.0001 |
| SUBSAMP(TRT) | 10 | 15.77777778 | 0.53 | 0.8490 |

TESTS OF HYPOTHESES USING THE ANOVA MS FOR BLOCK*TRT AS AN ERROR TERM

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| TRT | 4 | 96.53333333 | 0.65 | [illegible]439 |

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBSAMP(TRT) AS AN ERROR TERM

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| BLOCK*TRT | 8 | 297.86666667 | 23.60 | 0.0001 |

Appendix C.3.

TURBIDIMETRIC STABILITIY - CAPILLARY WET 6 TO 12 DEPTH 22:15 TUESDAY, JULY 4, 1989 1

ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

| CLASS | LEVELS | VALUES |
|---|---|---|
| BLOCK | 3 | 1 2 3 |
| TRT | 5 | 1 2 3 4 5 |
| SUBSAMP | 3 | 1 2 3 |

NUMBER OF OBSERVATIONS IN DATA SET = 45

TURBIDIMETRIC STABILITIY - CAPILLARY WET 6 TO 12 DEPTH 22:15 TUESDAY, JULY 4, 1989 2

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: T20

| SOURCE | DF | SUM OF SQUARES | MEAN SQUARE | F VALUE | PR > F | R-SQUARE | C.V. |
|---|---|---|---|---|---|---|---|
| MODEL | 24 | 914.31111111 | 38.09629630 | 5.17 | 0.0002 | 0.8612[illegible] | 7.96[illegible] |
| ERROR | 20 | 147.33333333 | 7.36666667 | | ROOT MSE | | T20 MEAN |
| CORRECTED TOTAL | 44 | 1061.64444444 | | | 2.71416040 | | 34.08888889 |

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| BLOCK | 2 | 149.91111111 | 10.17 | 0.0009 |
| TRT | 4 | 194.31111111 | 6.59 | 0.0015 |
| BLOCK*TRT | 8 | 430.75555556 | 7.31 | 0.0002 |
| SUBSAMP(TRT) | 10 | 139.33333333 | 1.89 | 0.1080 |

TESTS OF HYPOTHESES USING THE ANOVA MS FOR BLOCK*TRT AS AN ERROR TERM

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| TRT | 4 | 194.31111111 | 0.90 | [redacted] |

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBSAMP(TRT) AS AN ERROR TERM

| SOURCE | DF | ANOVA SS | F VALUE | PR > F |
|---|---|---|---|---|
| BLOCK*TRT | 8 | 430.75555556 | [illegible] | [0.0248] |